Higgs Interactions in New Physics

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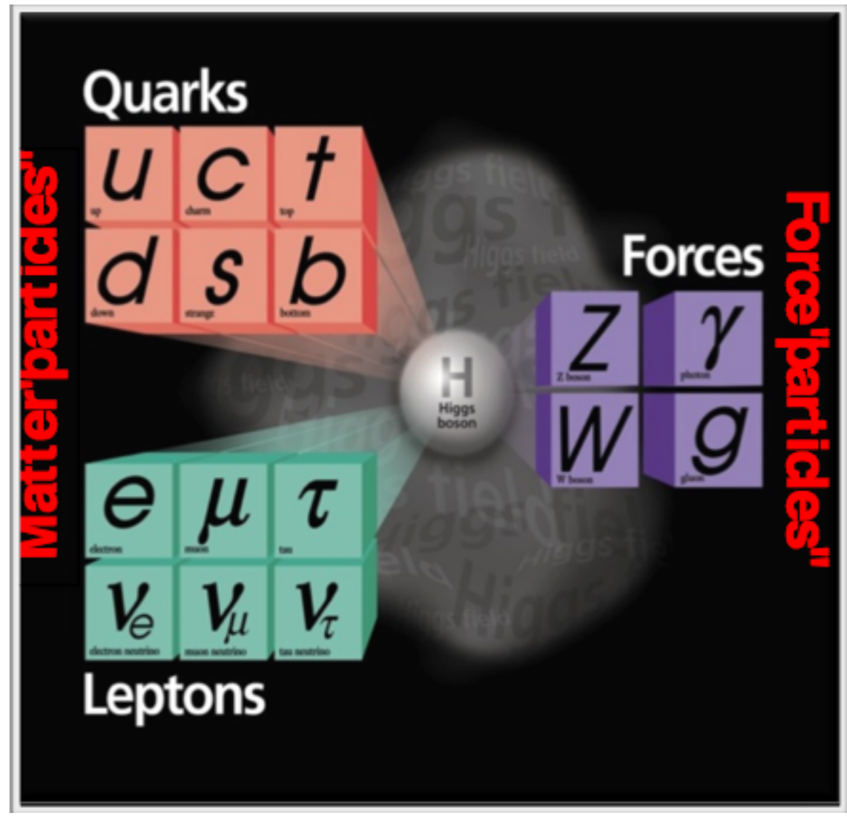
What can Higgs Boson tell us?

Higgs-self couplings
HHH and *HHHH*

HVV coupling

Relation between
M_W and M_Z
(custodial Symmetry)



HFF coupling

Magnitude and CP

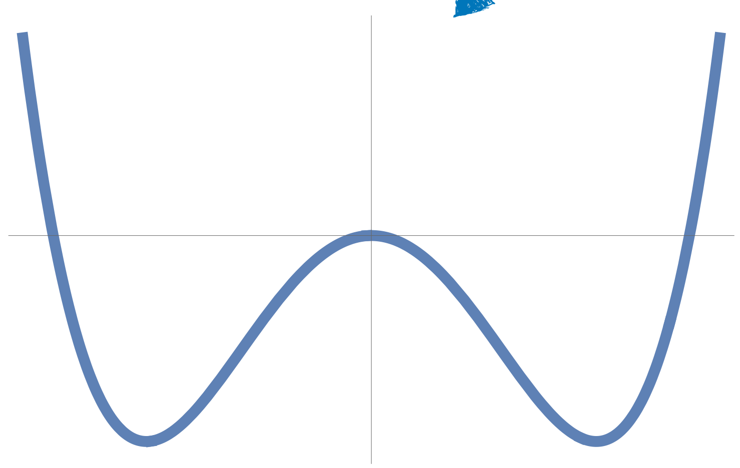
Relation between
HVV and *HHVV*
couplings

The Higgs boson is important not only for EWSB, but also as a WINDOW to NP beyond the SM.

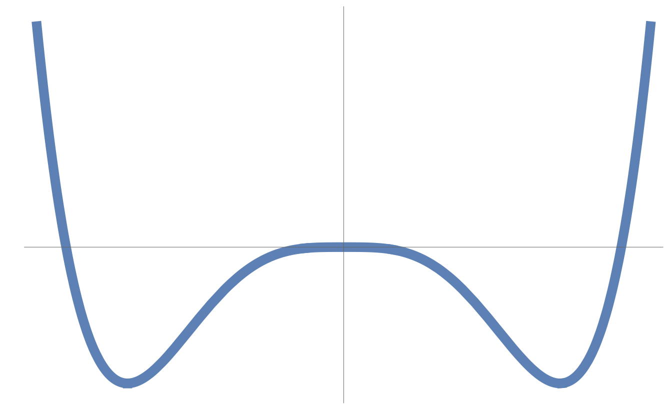
1. Higgs-self Interaction

(probing potential at electroweak scale)

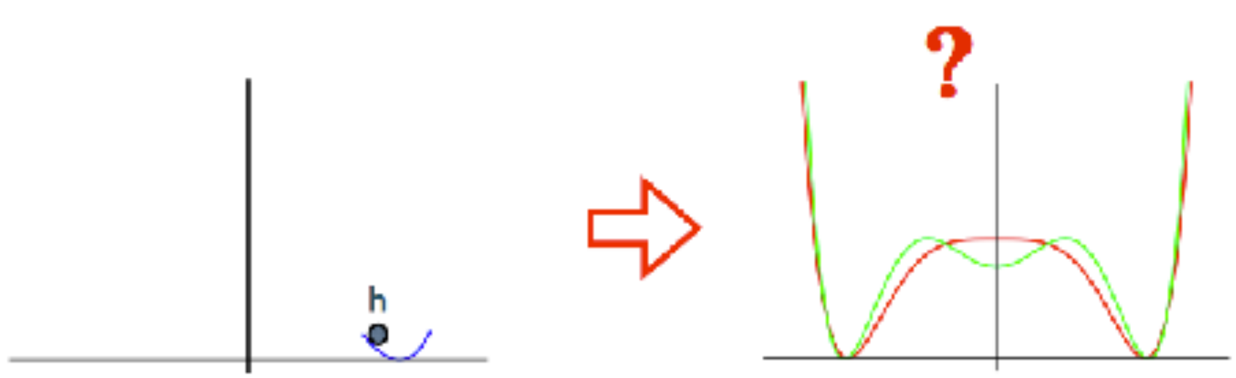
$$V(\phi) = -\mu^2\phi^2 + \lambda(\mu)\phi^4 + \frac{\kappa(\mu)}{\Lambda^2}\phi^6 + \cdots$$



Coleman-Weinberg Higgs

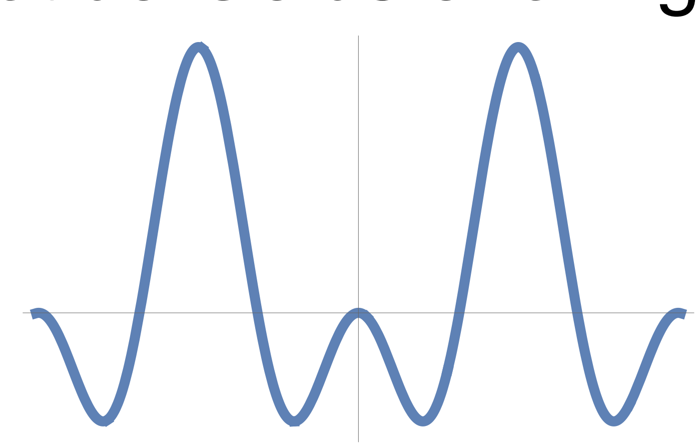


$$V(\phi) = \lambda(\phi^\dagger\phi)^2 + \epsilon(\phi^\dagger\phi)^2 \log\frac{\phi^\dagger\phi}{\mu^2}$$



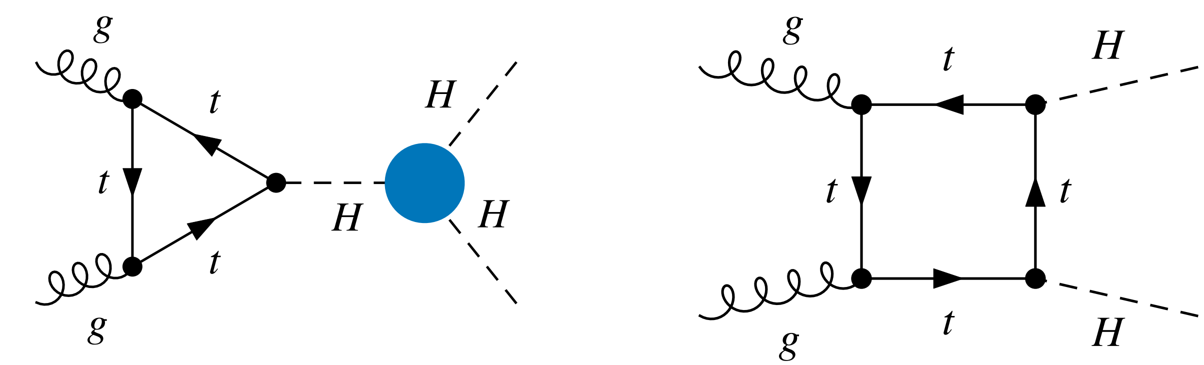
The LHC

Pseudo-Goldstone Higgs

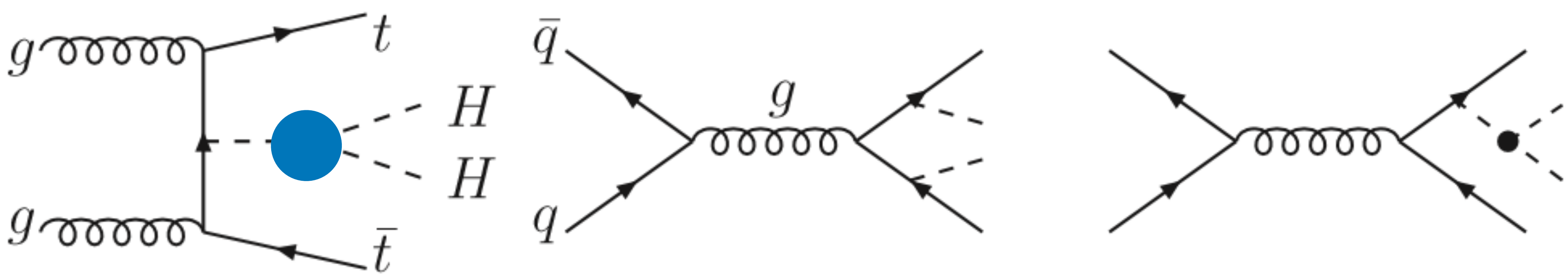


$$V(\phi) = a\sin^2(\phi/f) + b\sin^4(\phi/f)$$

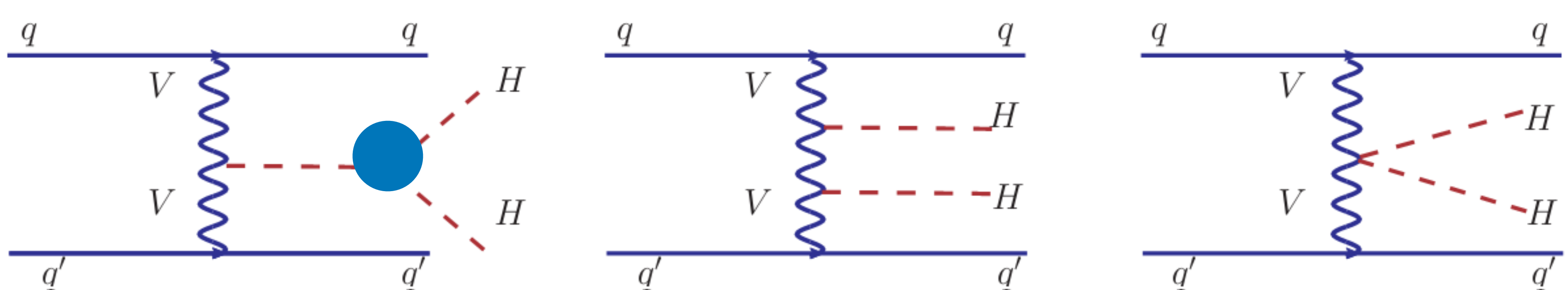
Measuring *HHH* coupling via Higgs Pair Productions



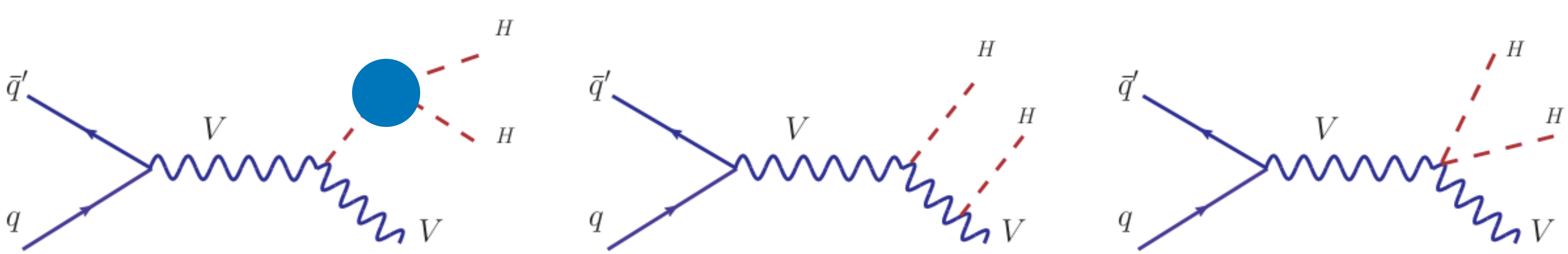
$gg \rightarrow HH$



$gg \rightarrow t\bar{t}HH$

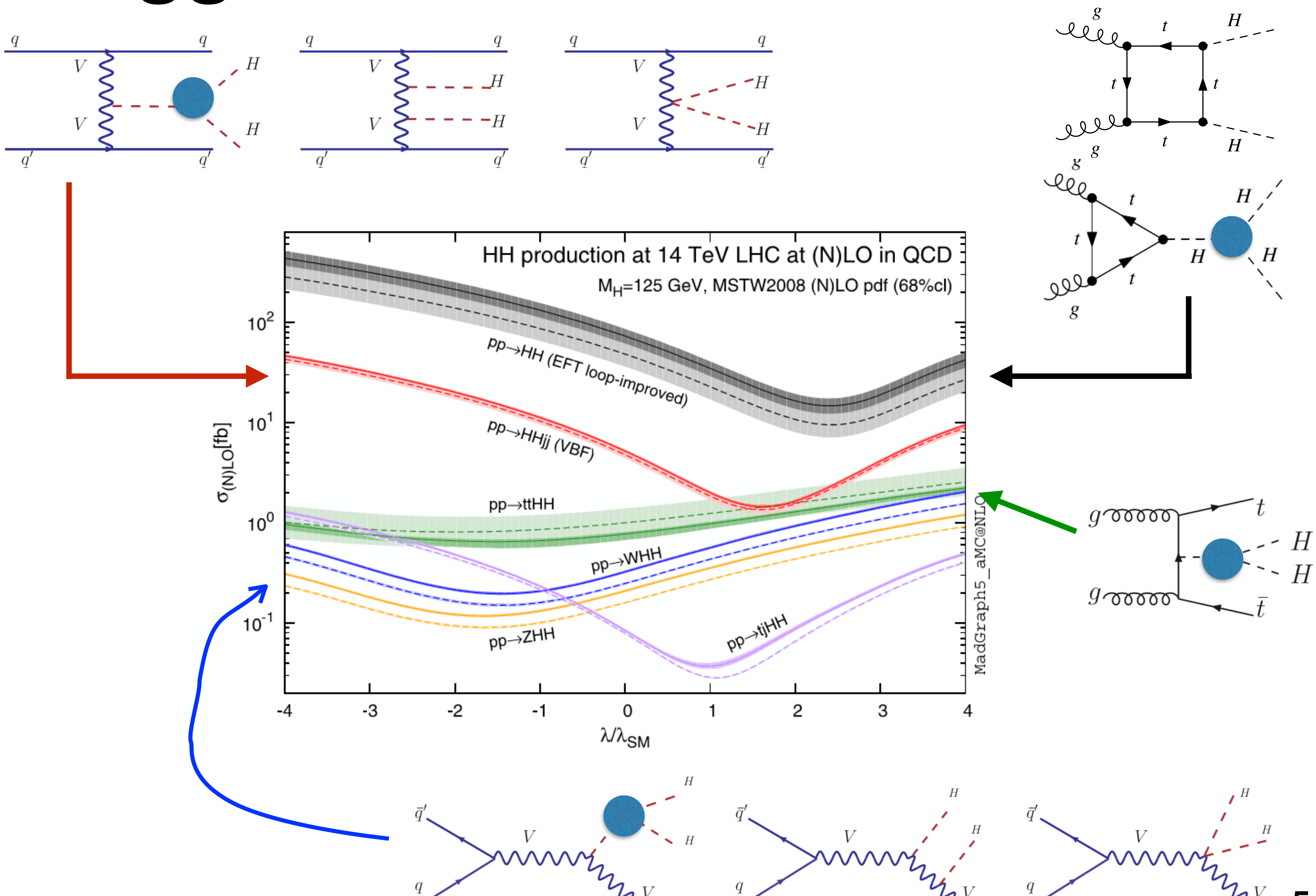


$qq' \rightarrow HHqq'$

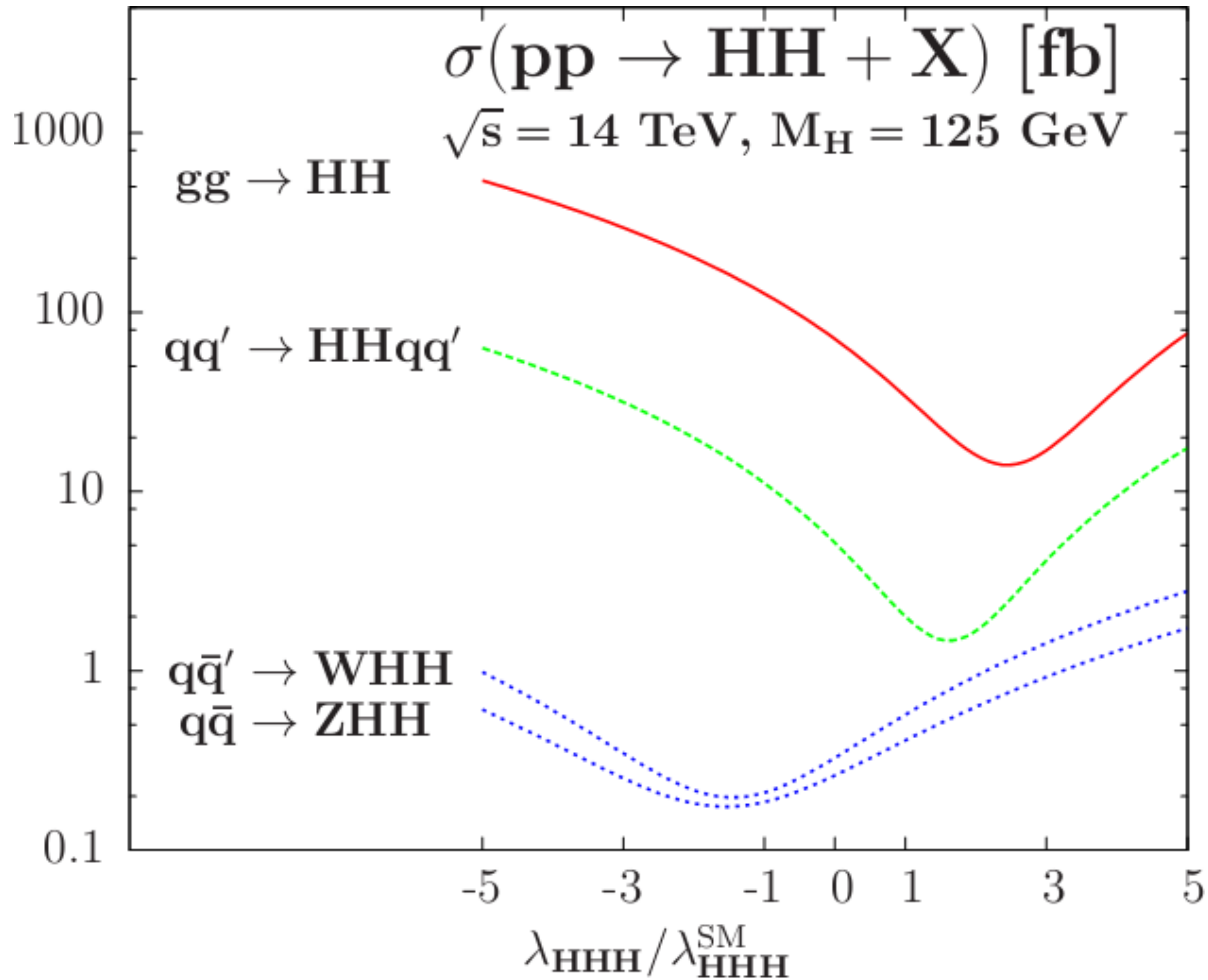


$q\bar{q}' \rightarrow VHH$

Higgs Boson Pair Production



Sensitive to *HHH* coupling very differently



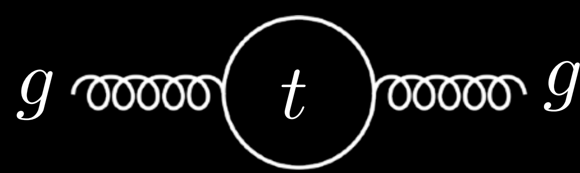
J. Baglio, A. Djouadi et al. JHEP 1304(2013)51

Sensitivity to HHH coupling: 1) gg->HH

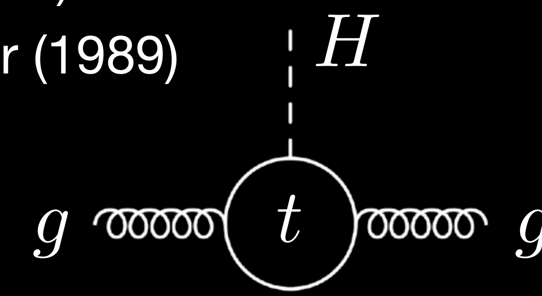
Low Energy Theorem

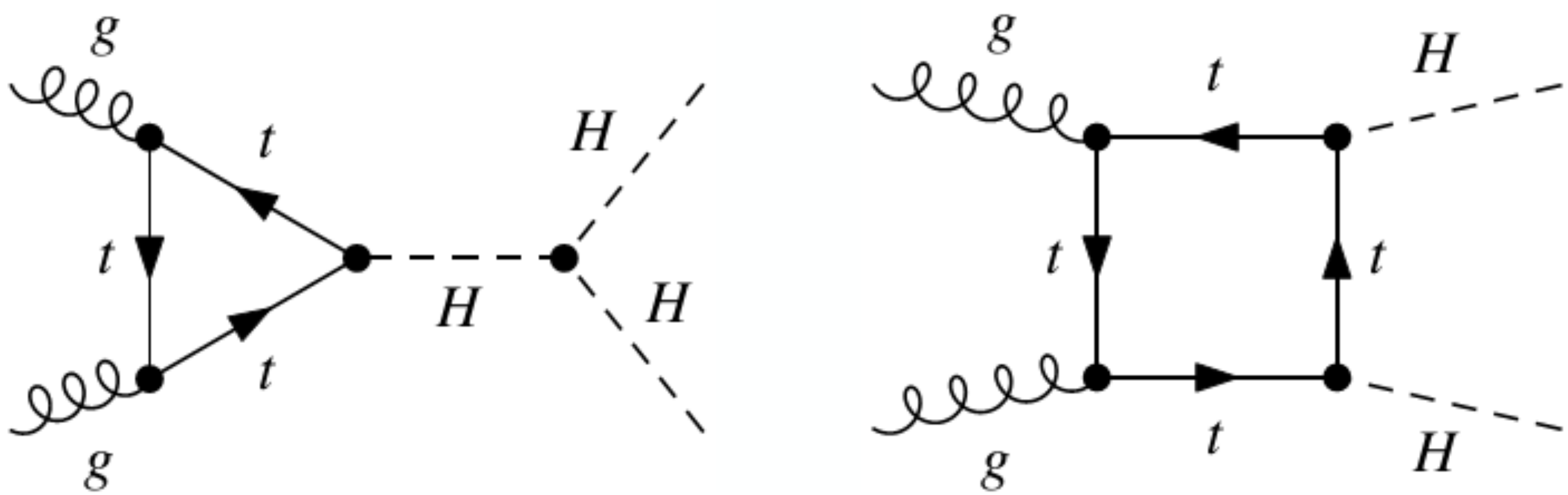
Shiftman, et al (1979)

Dawson and Haber (1989)



$$\sim -\frac{\alpha_s}{24\pi} G^a_{\mu\nu} G^{\mu\nu}_a \log\frac{\Lambda^2}{m_t^2} \quad \xrightarrow{\; y_t \frac{\partial}{\partial m_t} \;} \quad \frac{\alpha_s}{12\pi v} G^a_{\mu\nu} G^{\mu\nu}_a H$$





$$-\frac{\alpha_s}{24\pi} G^{a,\mu\nu} G^a_{\mu\nu} \sum_n \frac{y_t^n h^n}{n!} \frac{\partial^n}{\partial m_t^n} \log\left(\frac{\Lambda_{UV}^2}{m_t^2}\right)$$

n=1

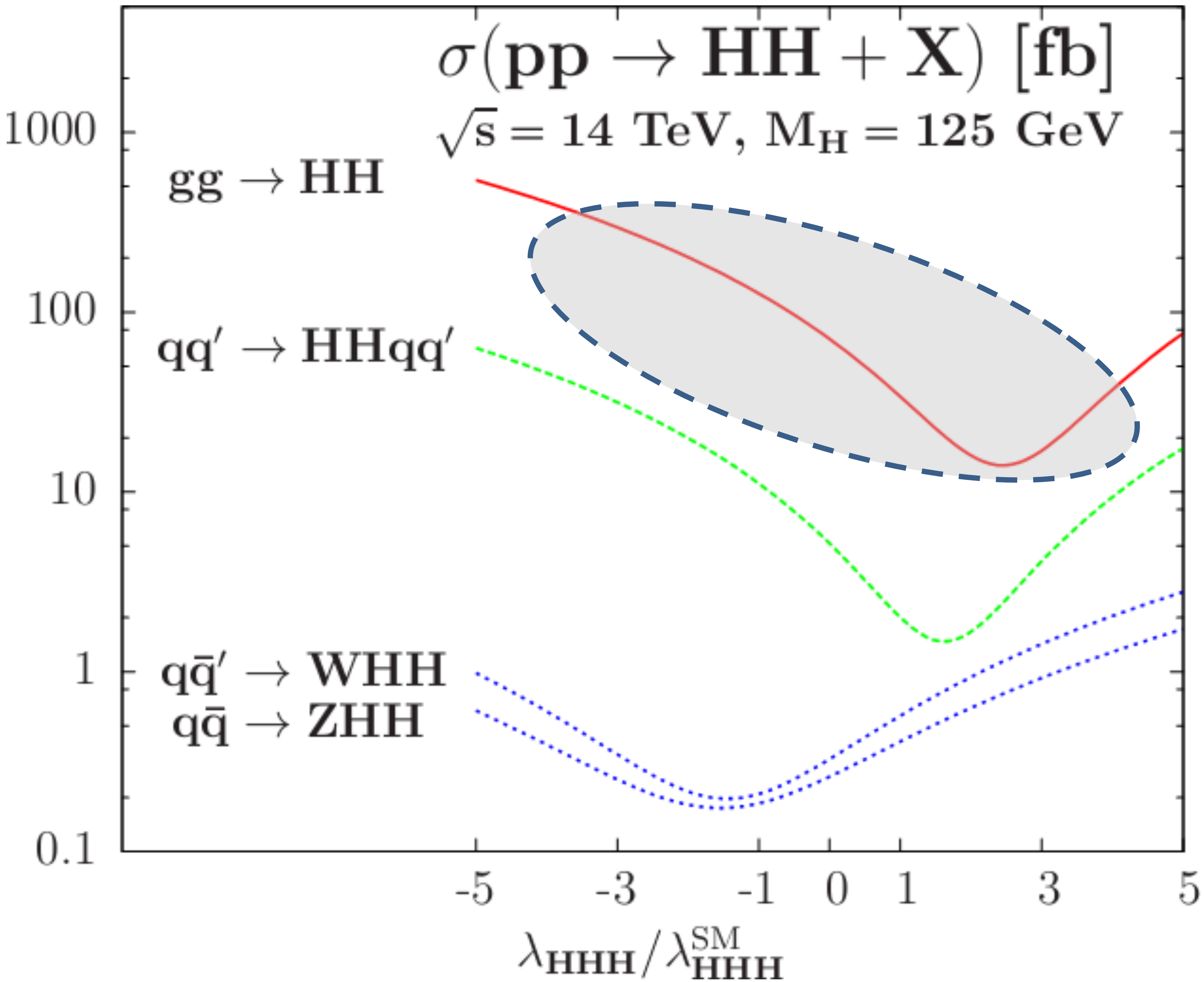
$$\frac{\alpha_s}{12\pi v} G^{a,\mu\nu} G^a_{\mu\nu} h$$

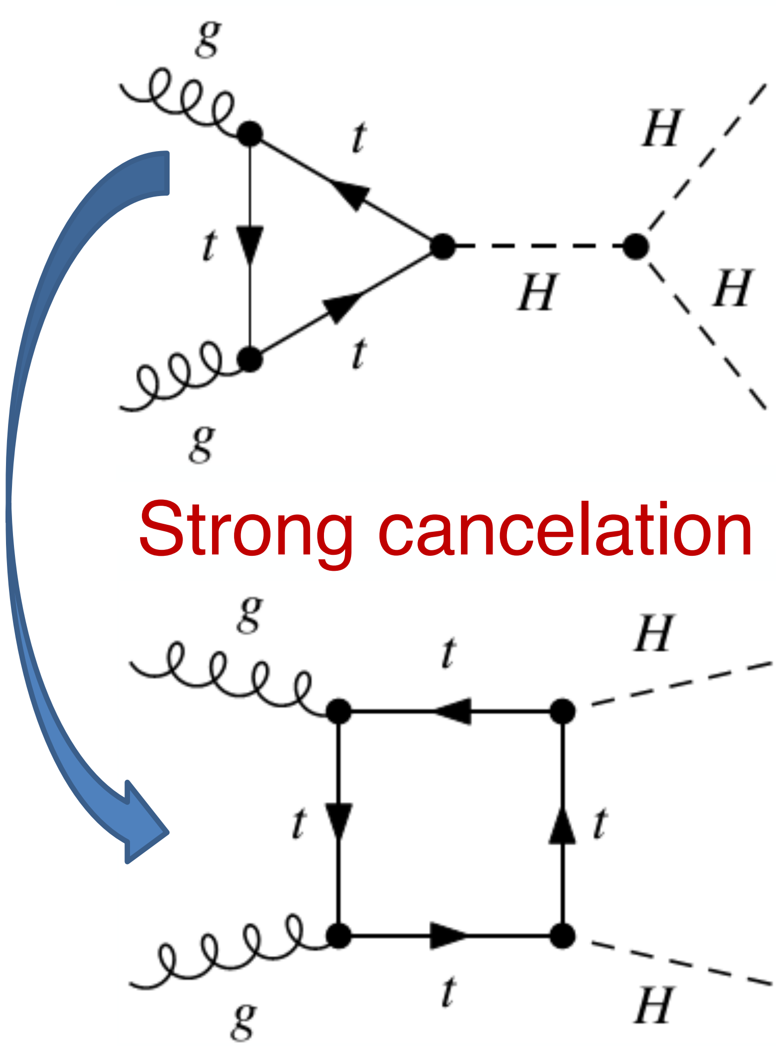
n=2

$$- \frac{\alpha_s}{24\pi v^2} G^{a,\mu\nu} G^a_{\mu\nu} h^2$$

Strong cancelation

Sensitivity to HHH coupling: 1) gg->HH



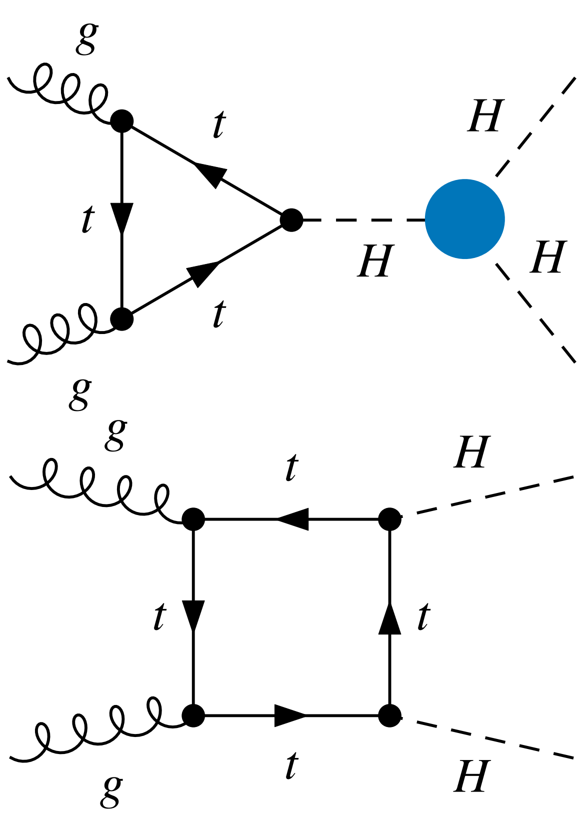


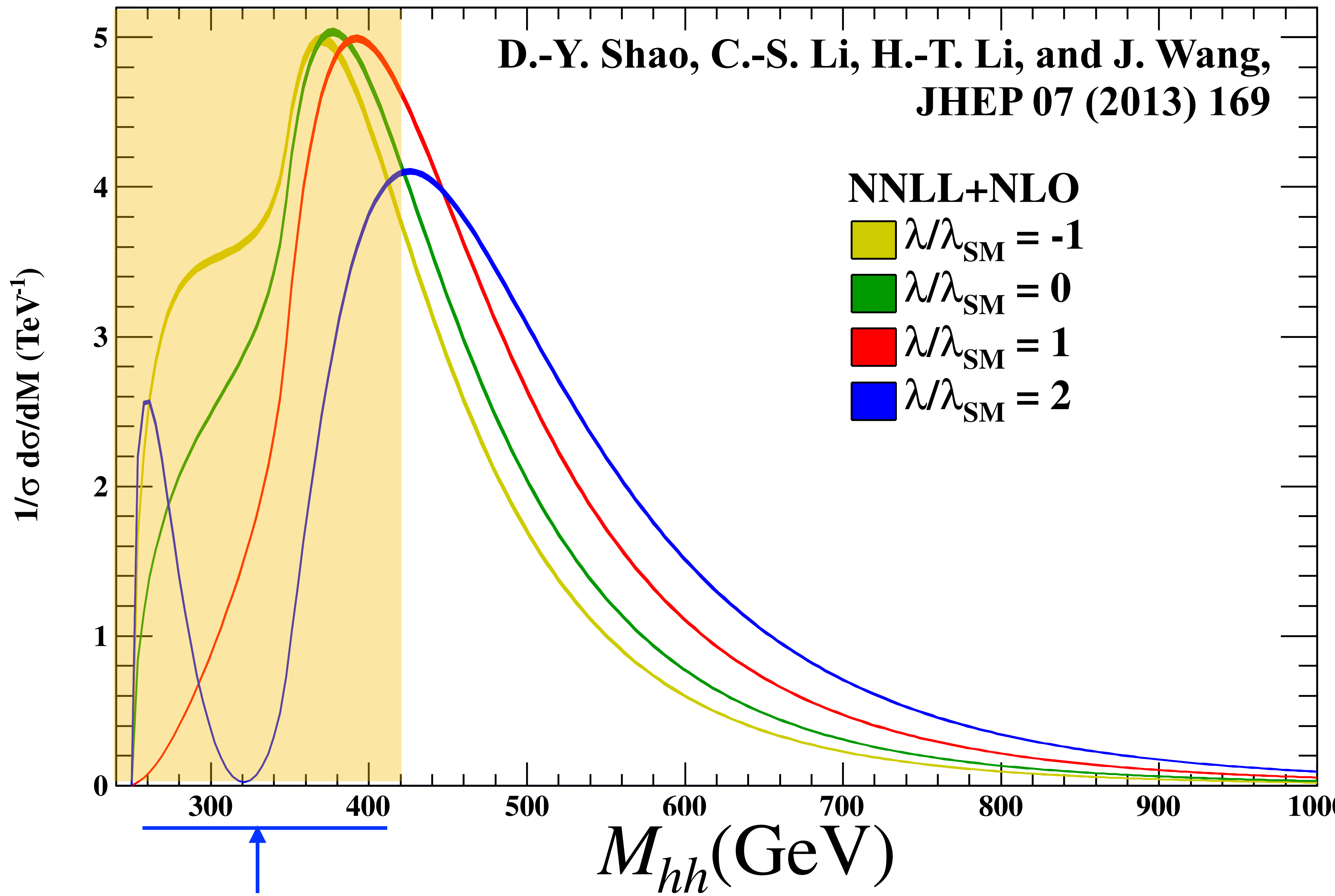
J. Baglio, A. Djouadi et al. JHEP 1304(2013)51

gg->HH: the leading channel

Unfortunately, it is not a easy job at the LHC or even at the SppC.

HH production

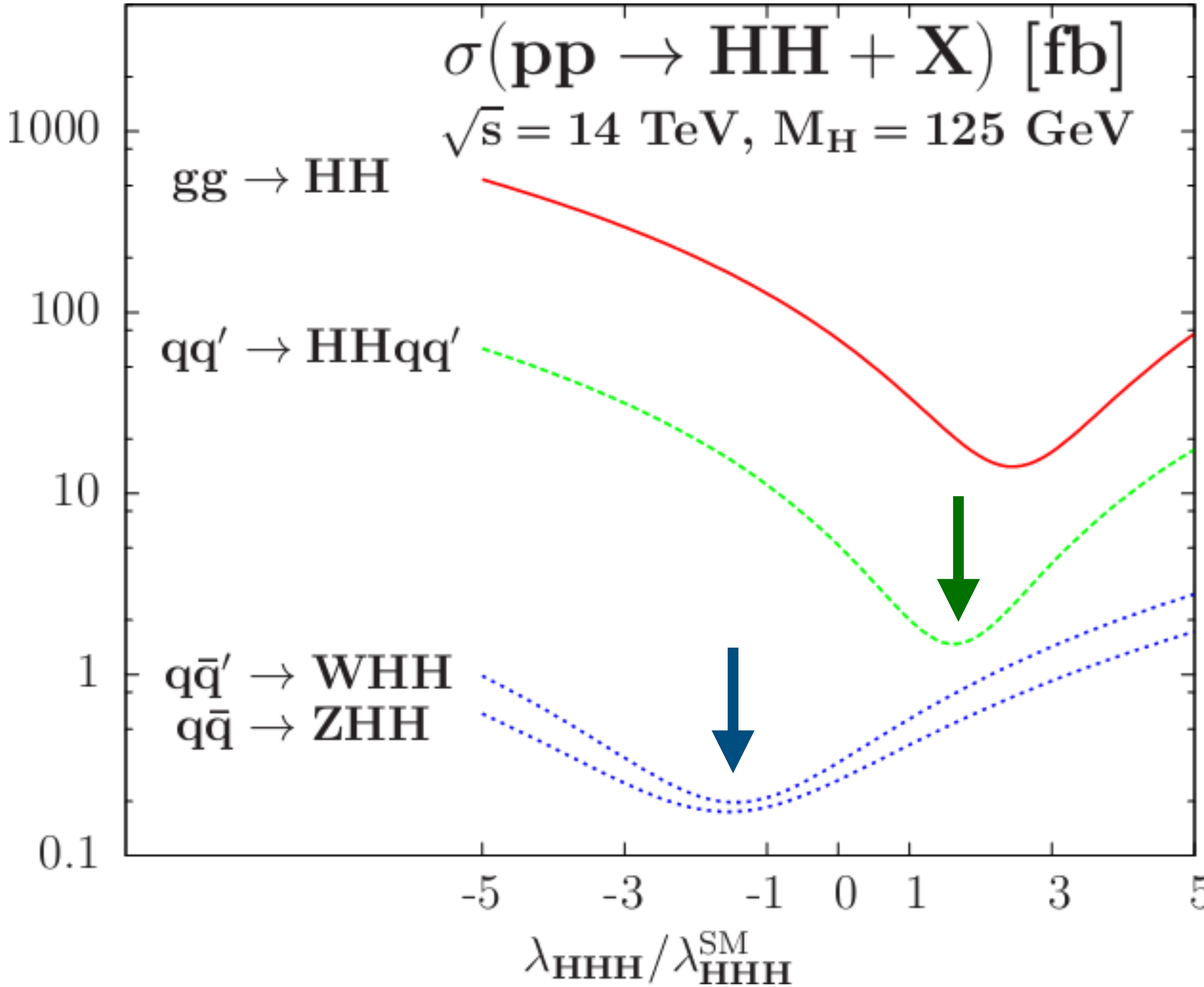


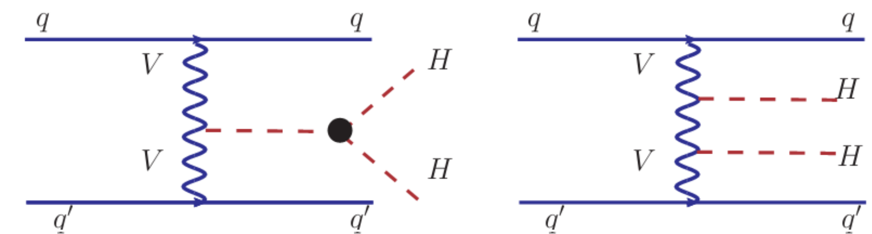


strong interference effects,

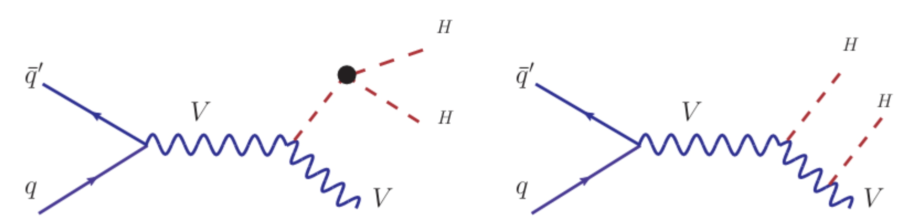
but not accessible at the LHC, due to hard cuts used by our experimental colleagues

Sensitivity to HHH coupling: 2) VBF and VHH



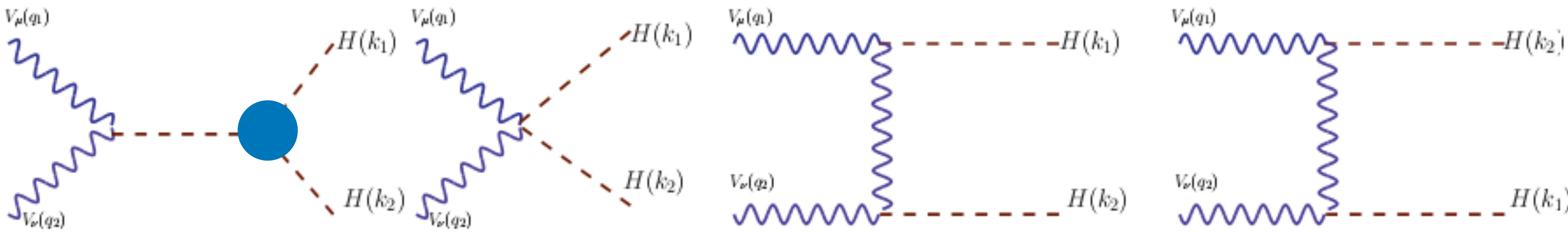


VBF and VHH are sensitive to HHH coupling differently



J. Baglio, A. Djouadi et al. JHEP 1304(2013)51

The VBF and VHH channels share the same subprocess but with different kinematics

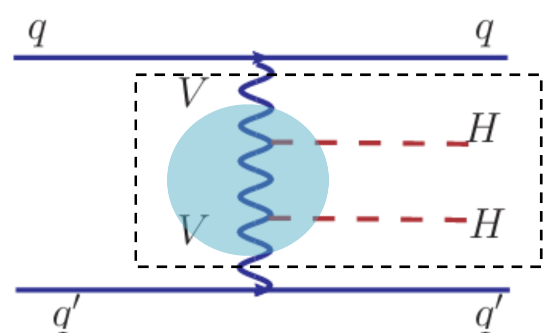


$$M^{\mu\nu} = \left[\frac{m_W^2}{v^2} \frac{6m_H^2}{\hat{s} - m_H^2} \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}} + \frac{2m_W^2}{v^2} + \frac{4m_W^4}{v^2} \left(\frac{1}{\hat{t} - m_W^2} + \frac{1}{\hat{u} - m_W^2} \right) \right] g^{\mu\nu} + \cdots$$

Near the threshold of Higgs-boson pairs

VBF:

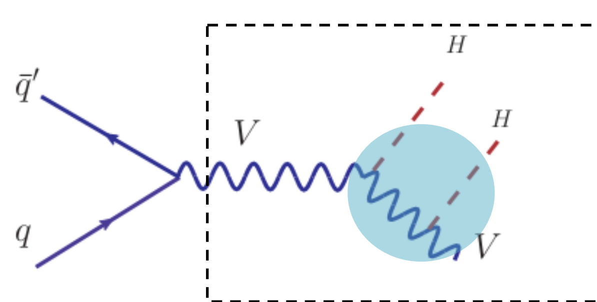
$$\hat{t} = \hat{u} = Q^2 < 0$$



$$M^{\mu\nu} \sim \frac{2m_V^2}{v^2} \left(\frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}} - 3 \right) g^{\mu\nu} + \cdots$$

VHH:

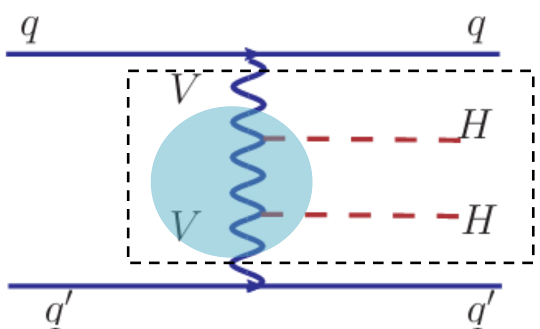
$$\hat{t} = \hat{u} = Q^2 > 0$$



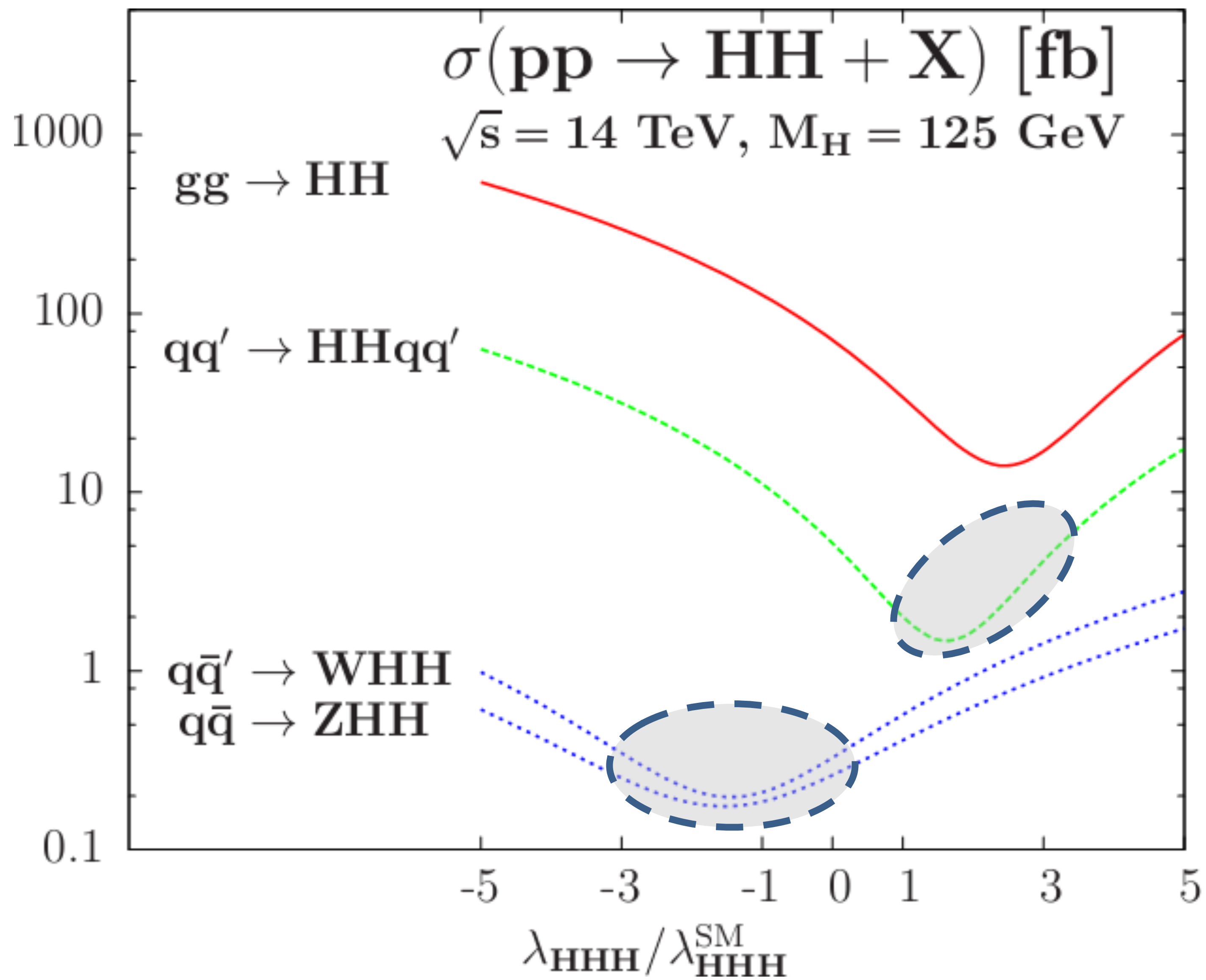
$$M^{\mu\nu} \sim \frac{2m_V^2}{v^2} \left(\frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}} + 1 \right) g^{\mu\nu} + \cdots$$

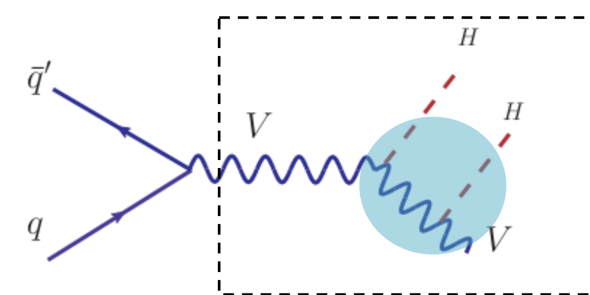
Sensitivity to HHH Coupling

VBF $$M^{\mu\nu} \sim \frac{2m_V^2}{v^2}\left(\frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}} - 3\right) g^{\mu\nu} + \cdots$$



$Q^2 < 0$

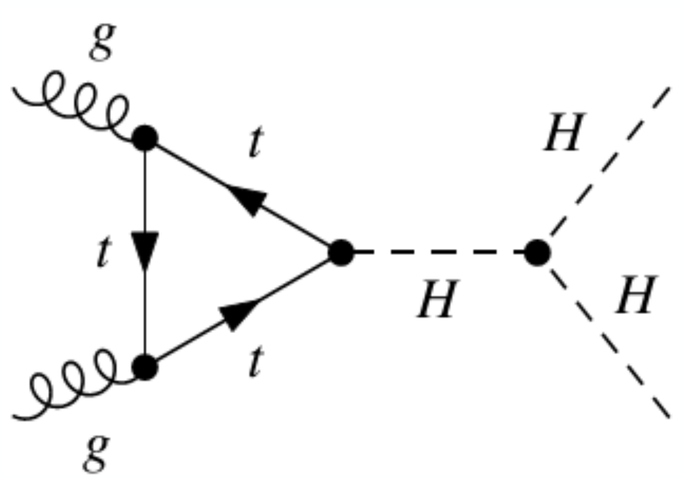




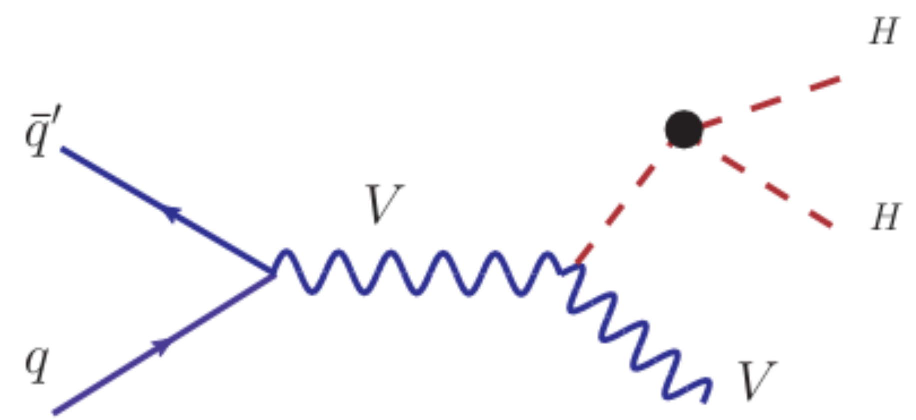
$Q^2 > 0$

VHH $$M^{\mu\nu} \sim \frac{2m_V^2}{v^2}\left(\frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}} + 1\right) g^{\mu\nu} + \cdots$$

HH and VHH @ HL-LHC



vs



Cross section: 34 fb >> Cross section: 0.57 fb

Final states: $bb\gamma\gamma$

$Br(bb\gamma\gamma) = 1.3 \times 10^{-3}$

Final states: $bbbb$

$Br(bbbblv) = 0.073$

$\sigma \times Br(bb\gamma\gamma) = 0.044$ fb $\approx$ $\sigma \times Br(bbbb\ell\nu) = 0.042$ fb

Huge backgrounds:

$b\bar{b}\gamma\gamma, c\bar{c}\gamma\gamma, b\bar{b}\gamma j, jj\gamma\gamma,$
$b\bar{b}jj, t\bar{t}, t\bar{t}\gamma, ZH, t\bar{t}H$

Main backgrounds:

Zbbbb, $Wbbbb, t\bar{t}, t\bar{t}j,$
$t\bar{t}H, t\bar{t}z, t\bar{t}$bb

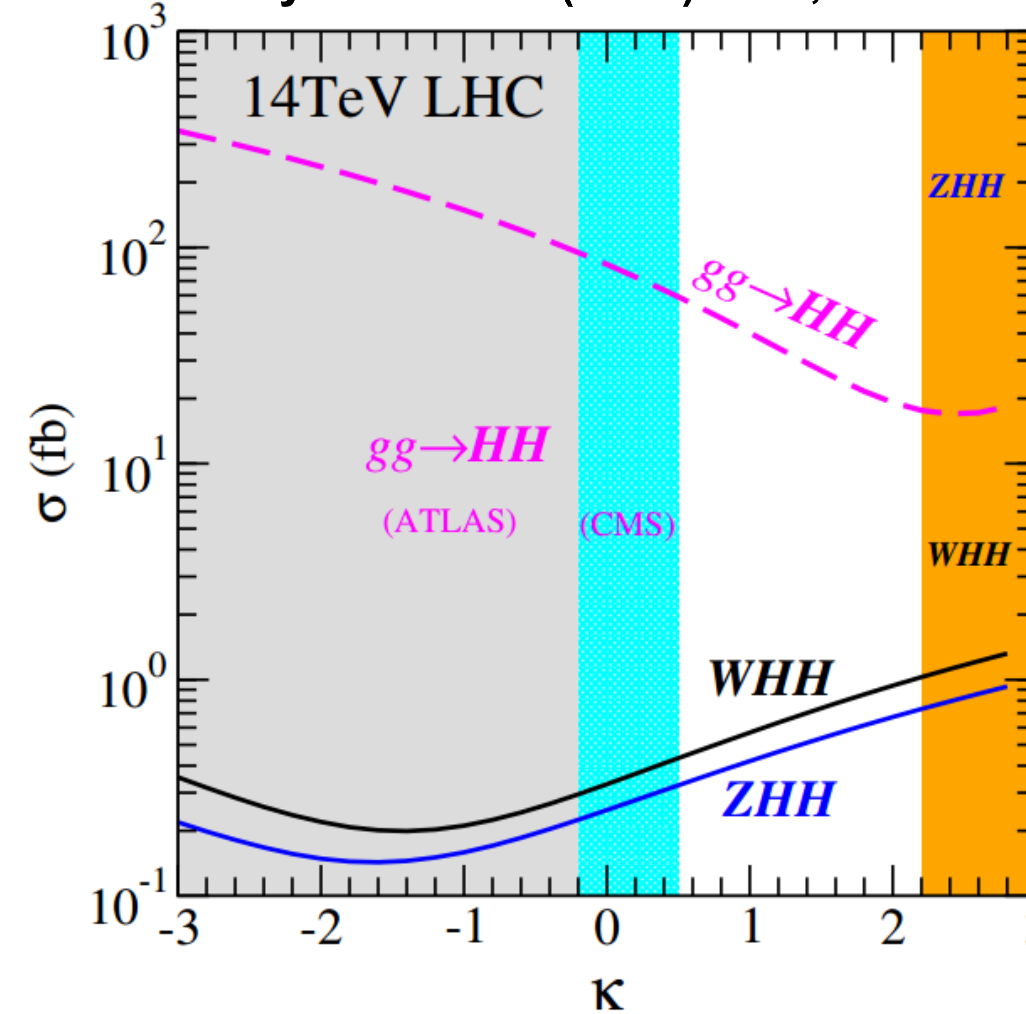
WHH and ZHH Productions

TABLE III: The sensitivity to $\lambda_{HHH} = \kappa\lambda_{HHH}^{SM}$ in several production channels of Higgs boson pairs at the HL-LHC.

	SM ($\kappa = 1$)	5σ discovery potential	2σ exclusion bound
WHH	1.29σ	$\kappa \leq -7.7, \ \kappa \geq 4.8$	$-5.1 \leq \kappa \leq 2.2$
ZHH	1.32σ	$\kappa \leq -8.1, \ \kappa \geq 4.8$	$-5.4 \leq \kappa \leq 2.2$
GF($b\bar{b}\gamma\gamma$) [42]	1.19σ	$\kappa \leq -4.5, \ \kappa \geq 8.1$	$-0.2 \leq \kappa \leq 4.9$
GF($b\bar{b}\gamma\gamma$) [43]	1.65σ	$\kappa \leq -2.6, \ \kappa \geq 6.3$	$0.5 \leq \kappa \leq 4.1$
VBF [20]	0.59σ	$\kappa \leq -1.7, \ \kappa \geq 5.0$	$-0.4 \leq \kappa \leq 3.5$
$t\bar{t}HH$ [21, 22]	1.38σ	$\kappa \leq -11.4, \kappa \geq 6.9$	$-7.2 \leq \kappa \leq 2.5$

The discovery potential of triple Higgs coupling in VHH production is **comparable** to other channels.

QHC, Liu, Yan,
Phys.Rev. D95 (2017) no.7, 073006

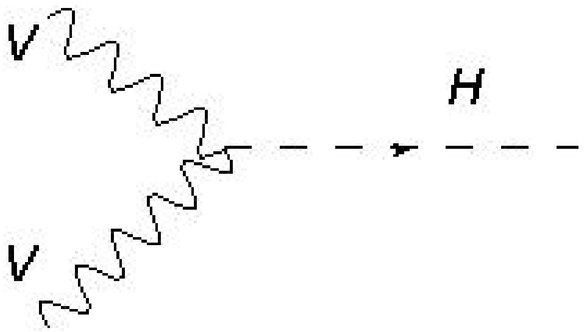


$$0.5 \leq \kappa \leq 2.2$$

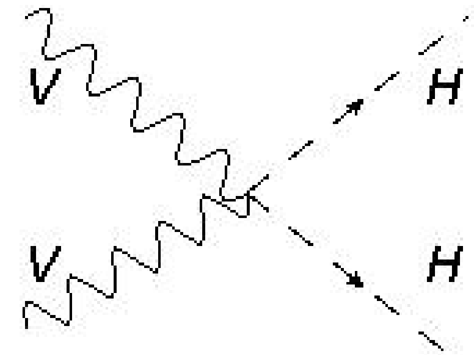
Nordstrom and Papaefstathiou (arXiv:1807.01571) include full detector effects and show that measuring HHH coupling via WHH and VHH channels is still challenging at the HL-LHC

HVV versus HHVV

SM predicts a definite ratio between HVV and HVV couplings



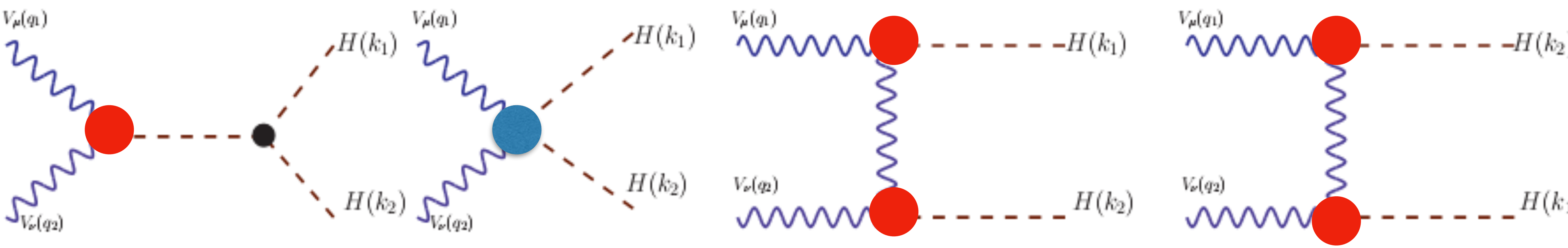
$$2i\frac{M_V^2}{v}g^{\mu\nu}$$



$$2i\frac{M_V^2}{v^2}g^{\mu\nu}$$

$$\frac{g_{hhVV}^{\mathrm{SM}}}{g_{hVV}^{\mathrm{SM}}}=\frac{1}{v} \qquad \frac{g_{hhVV}^{\mathrm{pNGB}}}{g_{hVV}^{\mathrm{pNGB}}}=\frac{1}{v}\frac{1-2\xi}{\sqrt{1-\xi}}$$

If the ratio is modified by NP, the unitarity of $VV \to HH$ is broken

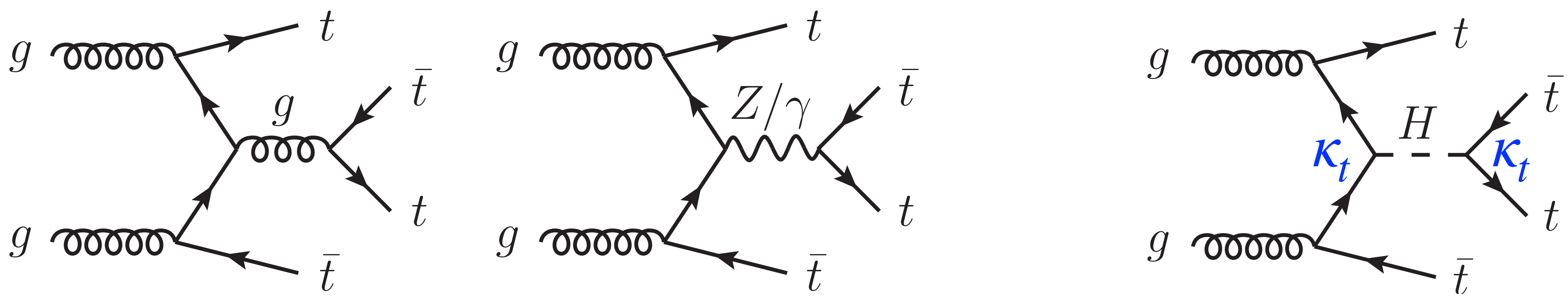


2. Top-Higgs Interactions

Four top quark production and the Higgs-top interaction

Barger, Stange, Phillips, 1991

QHC, Chen, Liu, 1602.01934



$$\sigma(t\bar{t}t\bar{t}) = \sigma^{\rm SM}(t\bar{t}t\bar{t})_{g/Z/\gamma} + \kappa_t^2 \sigma^{\rm SM}_{\rm int} + \kappa_t^4 \sigma^{\rm SM}(t\bar{t}t\bar{t})_H$$

LO

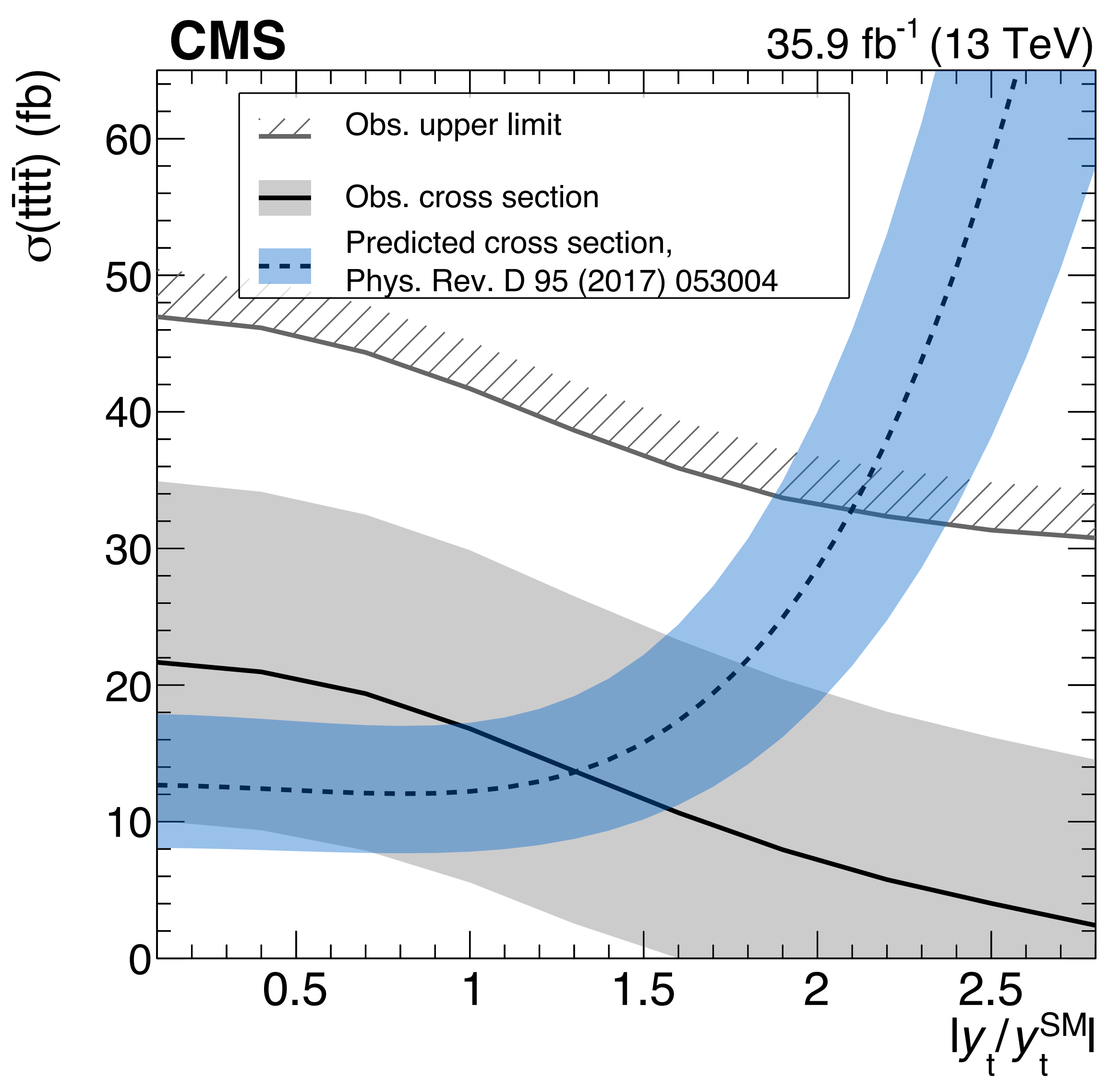
8 TeV	1.344	-0.224	0.171
13 TeV	9.997	-1.547	1.108
14 TeV	13.14	-2.007	1.515
27 TeV	115.1	-15.57	11.73
100 TeV	3276	-356.9	273.1

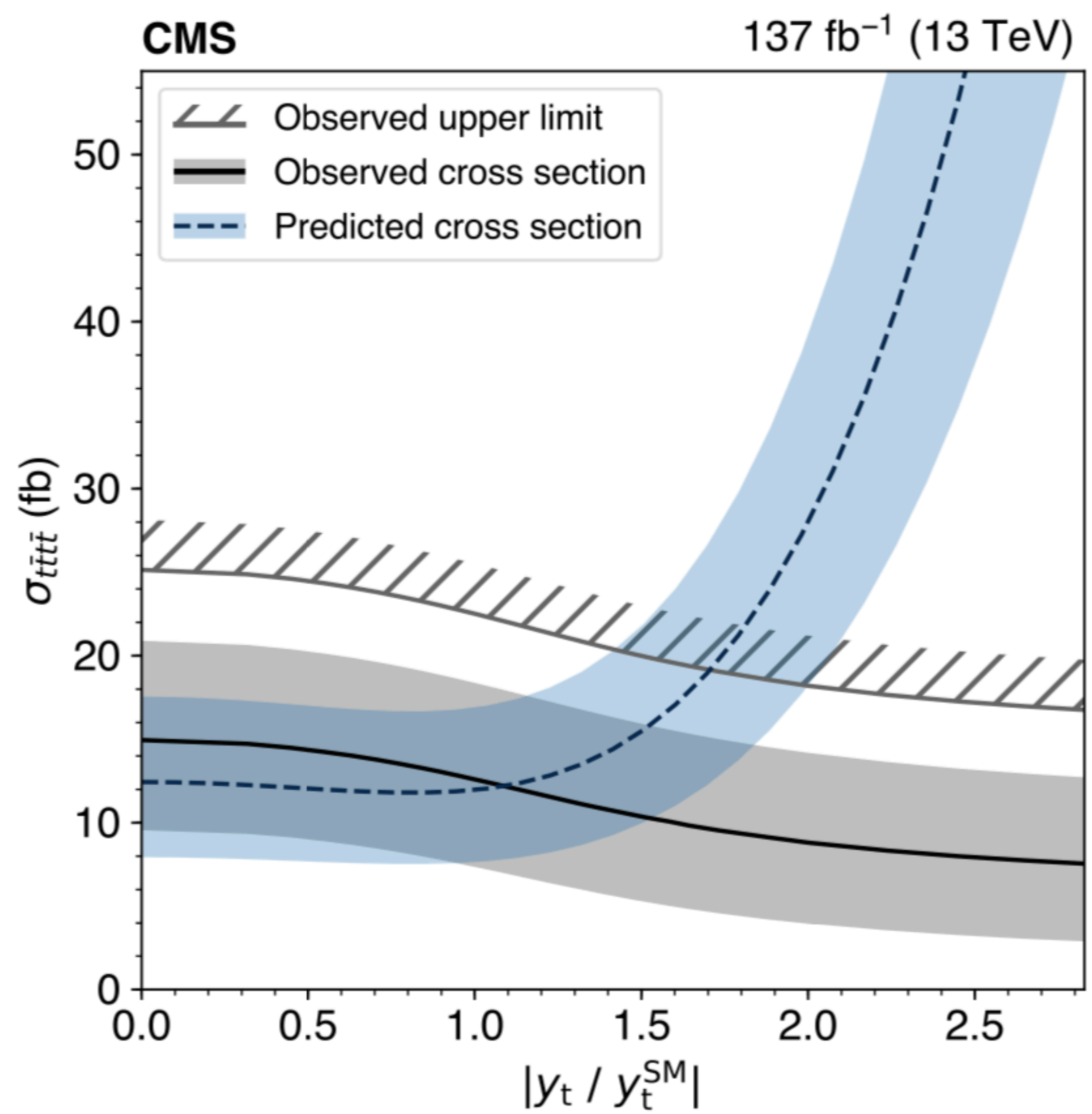
in unit of fb

NLO corrections: Bevilacqua, Worek (2012); Alwall et al (2014); Frederix, Pagani, Zaro (2017)

Four top quark productions

CP-even $\sigma(t\bar{t}t\bar{t}) = 9.997 - 1.547 \times y_t^2 + 1.108 \times y_t^4 \ \text{(fb)}$





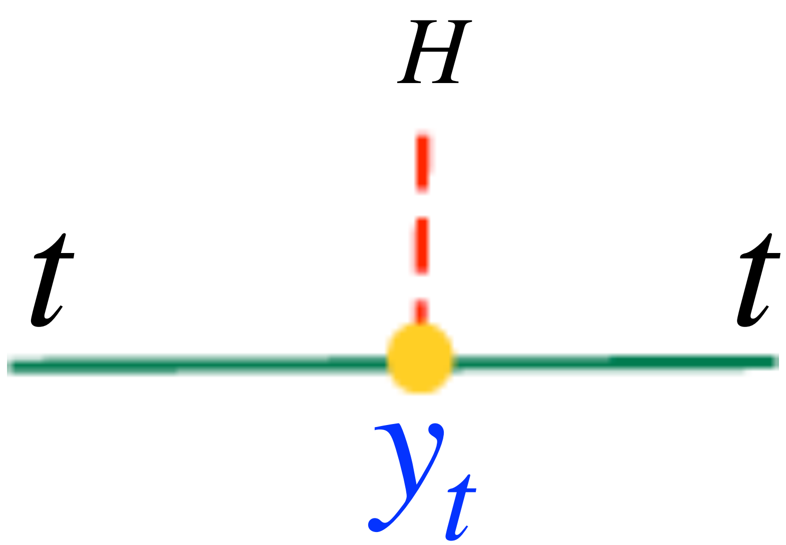
$y_t \leq 2.1 \times y_t^{SM}$ 1710.10614

$y_t \leq 1.7 \times y_t^{SM}$ 1908.06463 1909.05306

The channel is also sensitive to the CP property of top-Higgs interaction.

QHC, Chen, Liu, Zhang, Zhang, 1901.04567

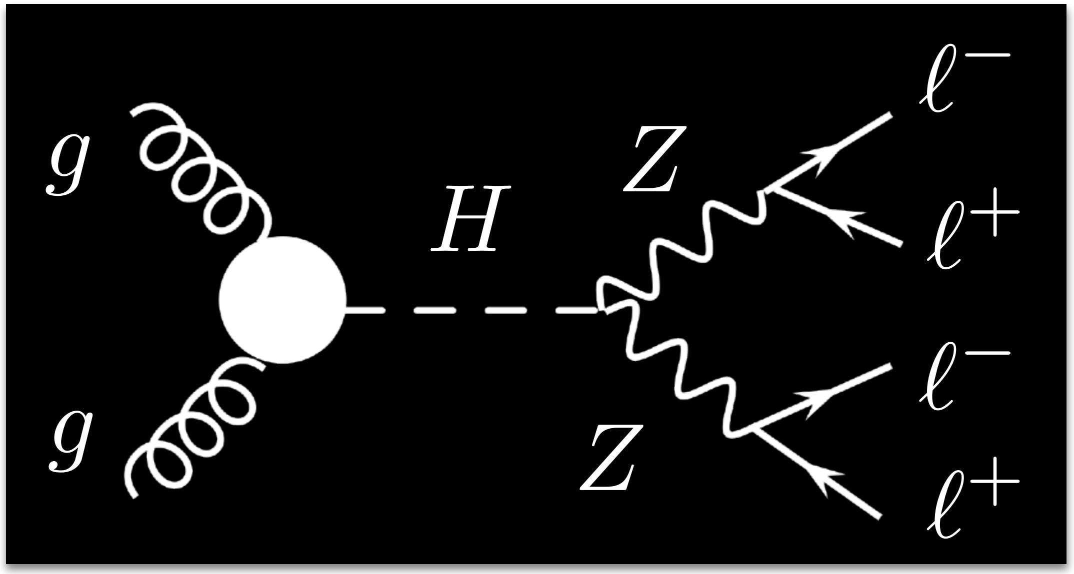
3. CP property of top-Higgs interaction



$$\mathscr{L}_{Ht\bar{t}} = -\frac{m_t}{v} H\bar{t}(a_t + ib_t\gamma_5)t$$

The CP property of the Hbb coupling is hard to measure due to the small bottom-quark mass.

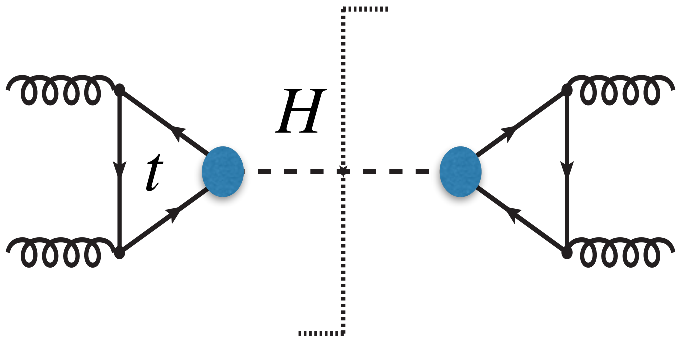
Different phase angle in the *hVV* and *hFF* vertices?



Higgs boson productions

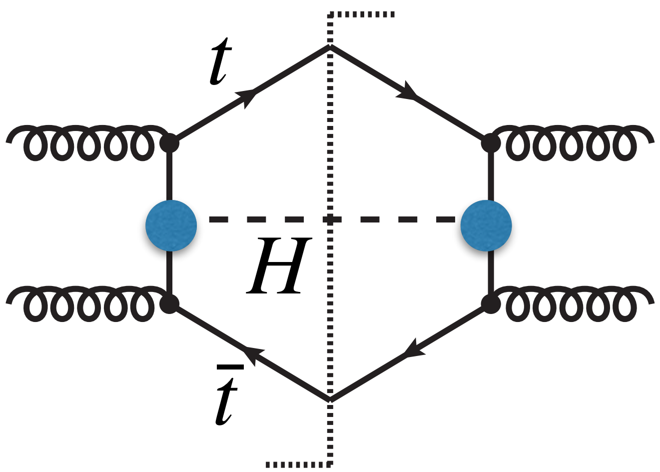
$$\mathscr{L}_{Ht\bar{t}} = -\frac{m_t}{v} H\bar{t}(a_t + ib_t\gamma_5)t$$

Boudjema, Godbole, Guadagnoli, Mohan, 1501.03157



$$\frac{\sigma(gg \to H)}{\sigma(gg \to H)_{\rm SM}} \sim a_t^2 + 2.26 b_t^2$$

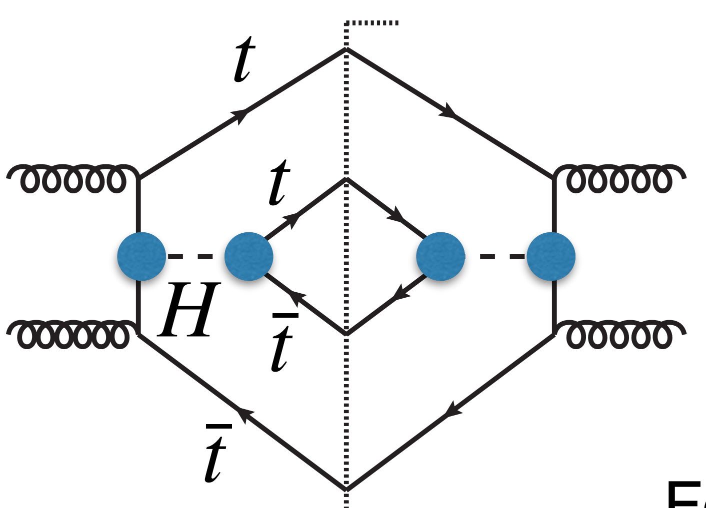
↑ pseudo-scalar dominates



$$\frac{\sigma(gg \to t\bar{t}H)}{\sigma(gg \to t\bar{t}H)_{\rm SM}} \sim a_t^2 + 0.42 b_t^2$$

(14TeV)

↑ scalar dominates



$$\sigma(t\bar{t}t\bar{t}) = 9.997 + 2.807 \times b_t^2 + 1.788 \times b_t^4$$

$$-1.547 \times a_t^2 + 1.108 \times a_t^4 \quad \text{(fb)}$$

Four tops — another way to probe top-Higgs coupling

CP property of top-Higgs interaction

$$\mathscr{L}_{Ht\bar{t}} = -\frac{m_t}{v} H\bar{t}(a_t + i b_t \gamma_5) t$$

Phys.Rev. D99 (2019) no.11, 113003
QHC, S.L Chen, Y. Liu, R. Zhang, Y. Zhang

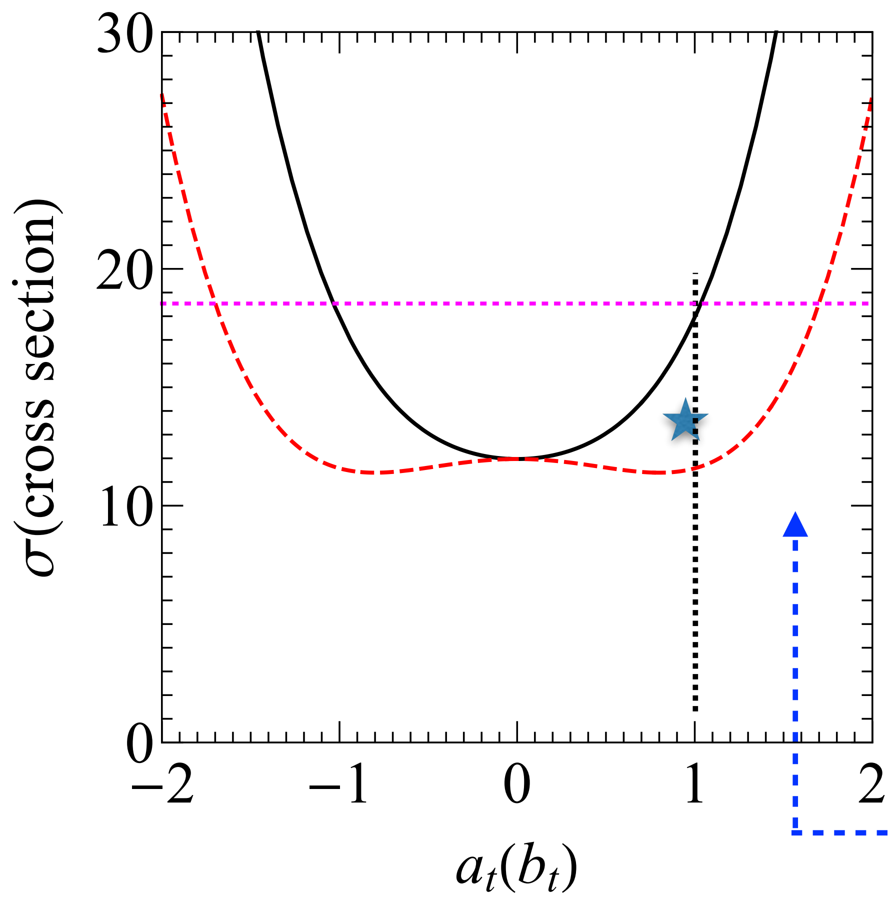
CP-odd
(a=0, b=1)

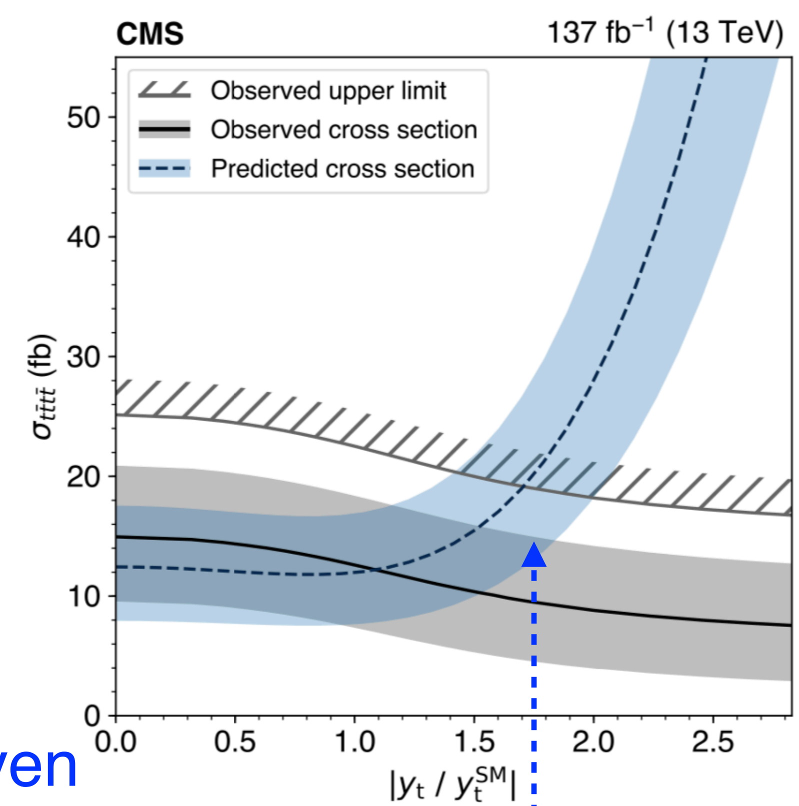
$$\sigma(t\bar{t}t\bar{t}) = 7.724 + 2.434 \times b_t^2 + 1.424 \times b_t^4 \text{ (fb)}$$

CP-even
(a=1, b=0)

$$\sigma(t\bar{t}t\bar{t}) = 7.724 - 1.164 \times a_t^2 + 0.910 \times a_t^4 \text{ (fb)}$$

$K_F = 1.55$ JHEP 02, 031 (2018) R. Frederix, D.Pagani, and M. Zaro



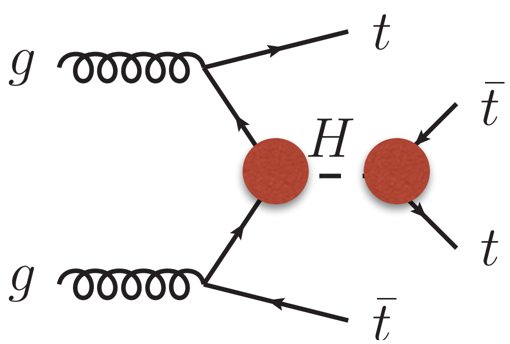


CP-even

$\kappa_t \leq 1.7$

$b_t \leq 1.03$ for a pure CP-odd coupling

Global analysis of Top-Higgs interaction

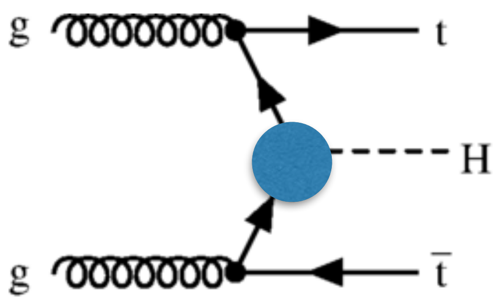


$$\sigma(t\bar{t}t\bar{t}) = 7.724 - 1.164a_t^2 + 2.434b_t^2 + 0.910a_t^4 + 2.183a_t^2b_t^2 + 1.424b_t^4$$

$K_F = 1.55$ JHEP 02, 031 (2018) R. Frederix, D.Pagani, and M. Zaro

137 fb^{-1}

CMS Collaboration arXiv:1908.06463

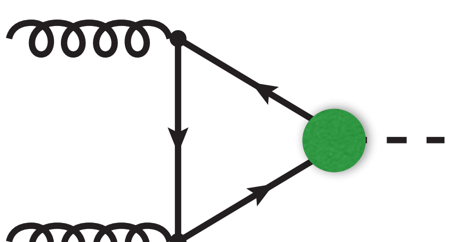


$$\frac{\sigma(gg \to t\bar{t}H)}{\sigma(gg \to t\bar{t}H)_{\rm SM}} = \left(a_t^2 + 0.46b_t^2\right)\frac{1}{R_\Gamma}$$

$$\mu_{t\bar{t}H} = 0.96^{+0.34}_{-0.31}$$

41.5 fb^{-1}

CMS-PAS-HIG-18-019



$$\frac{\sigma(gg \to H \to \gamma\gamma)}{\sigma(gg \to H \to \gamma\gamma)_{\rm SM}}$$

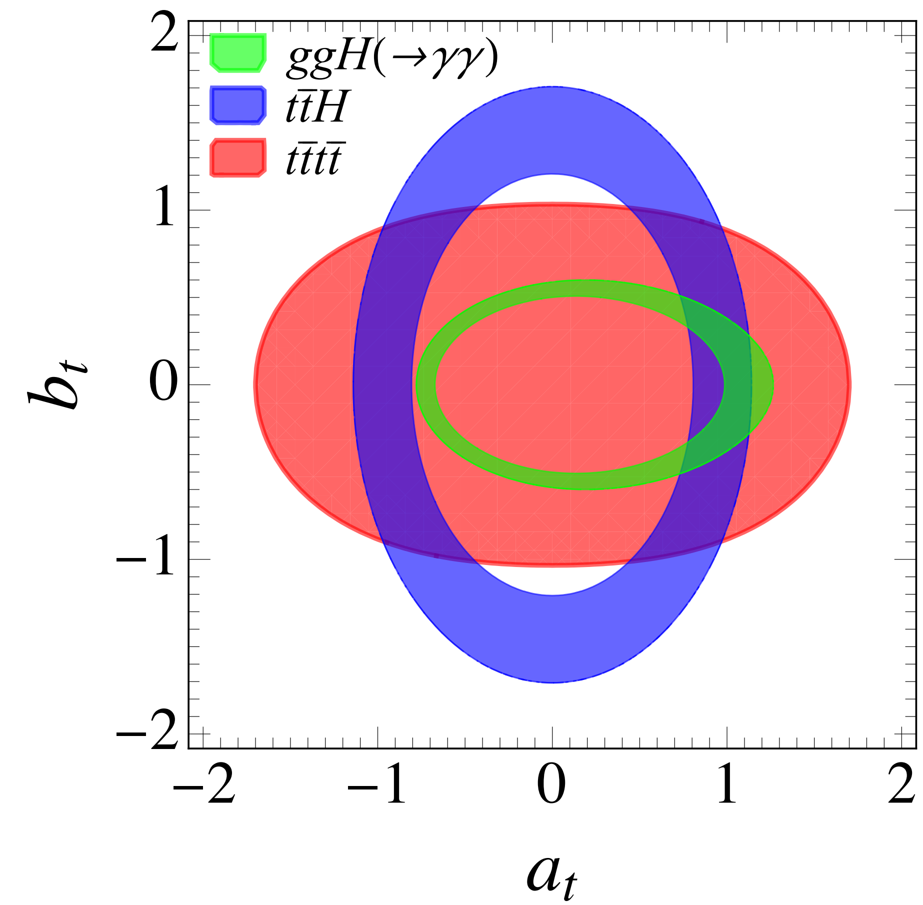
$$= \left(a_t^2 + 2.26b_t^2\right)$$

$$\times \frac{0.035(-7.2 + 1.83a_t^2) + 0.27b_t^2}{R_\Gamma}$$

36.3 fb^{-1}

Eur.Phys.J. C79 (2019) no.5, 421 CMS

$$\mu_{gg\to H\to\gamma\gamma} = 1.16^{+0.21}_{-0.18}$$



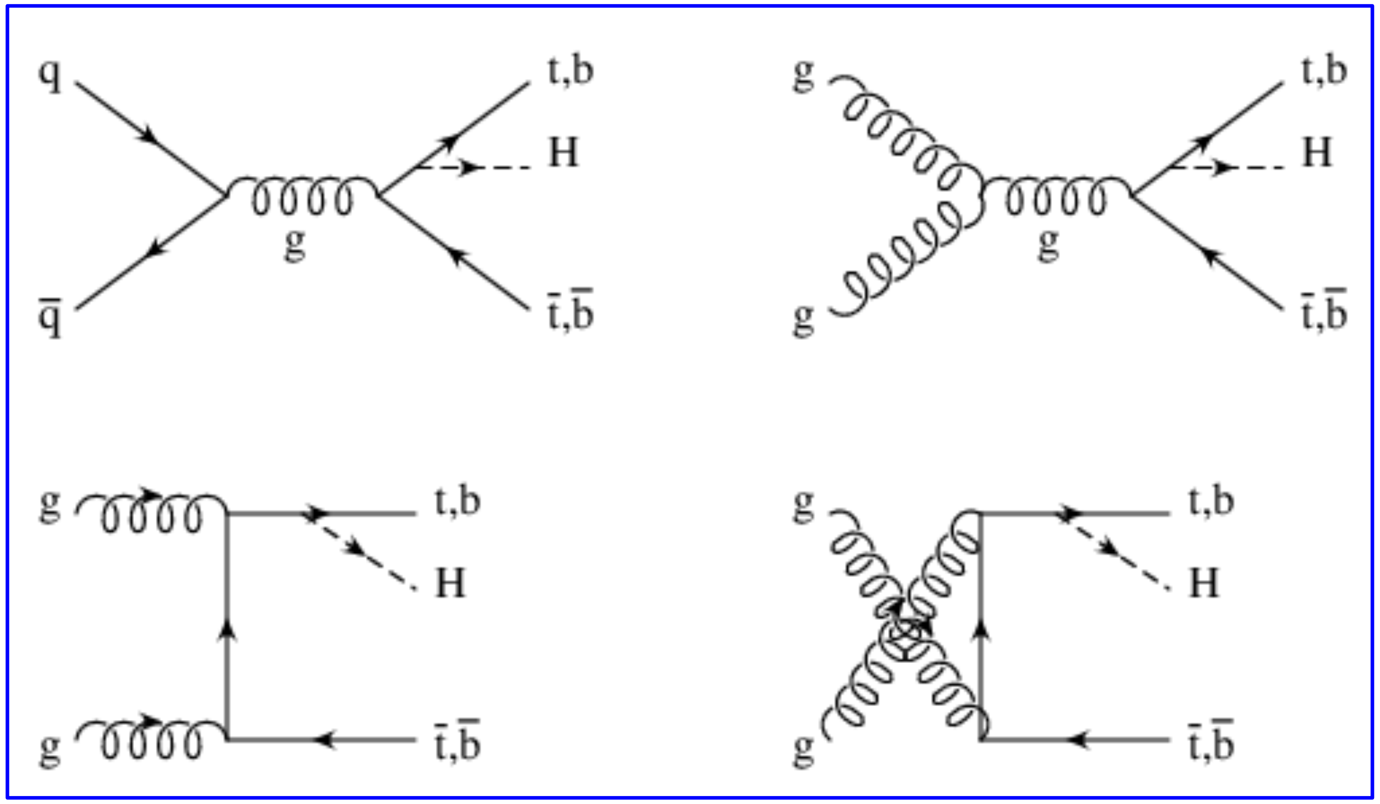
$$0.73 < a_t < 1.14, \quad -0.51 < b_t < 0.51$$

$$-\frac{\pi}{5} \leq \theta \leq \frac{\pi}{5}$$

We knew a little about the CP property of the Htt coupling **indirectly** from the cross sections of the single-Higgs production and ttH production.

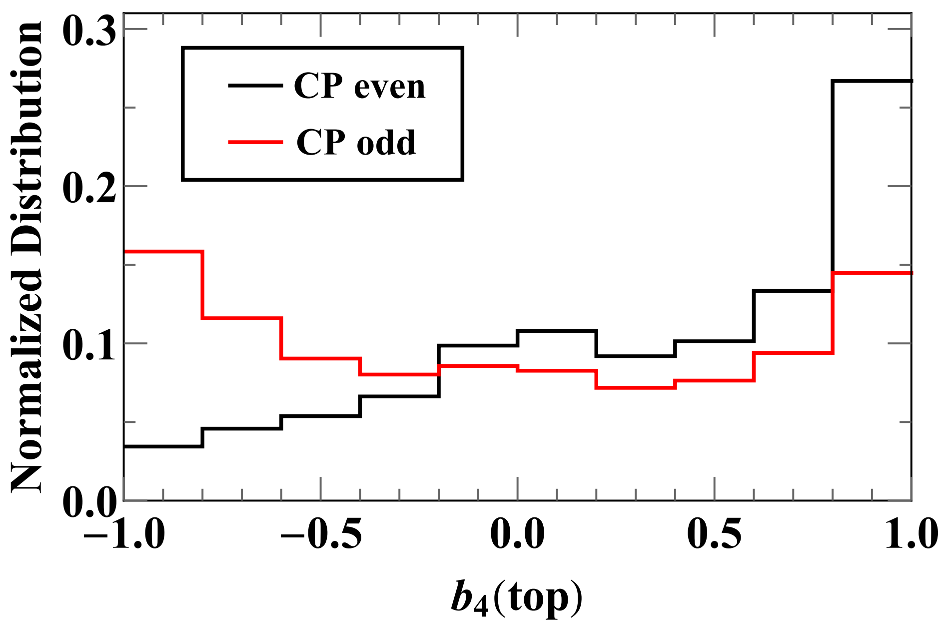
→ A pure CP-odd Htt coupling is not supported.

We still need measure it **directly** through the differential cross-sections of the ttH production.

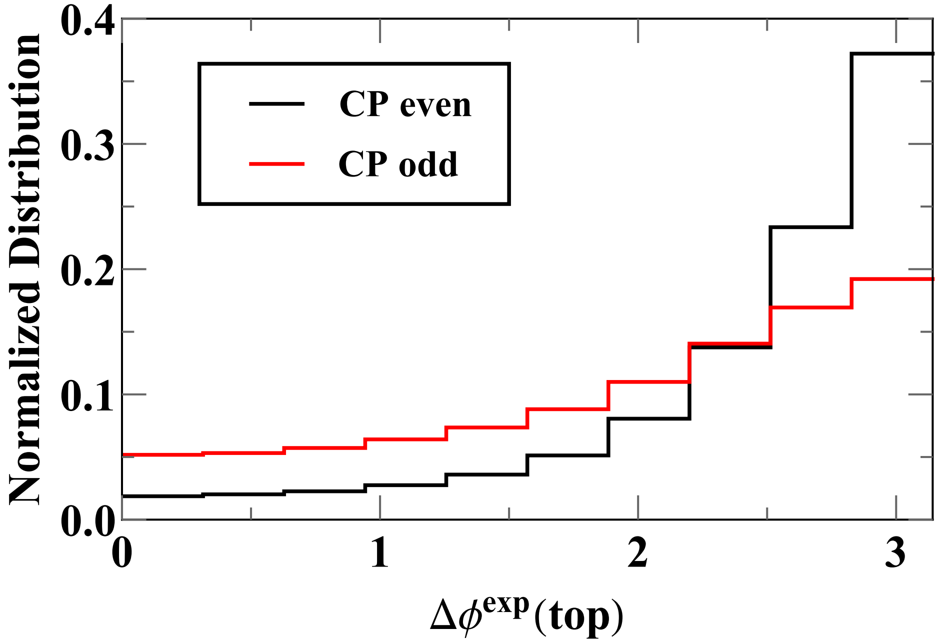


Measuring CP property of Htt coupling directly

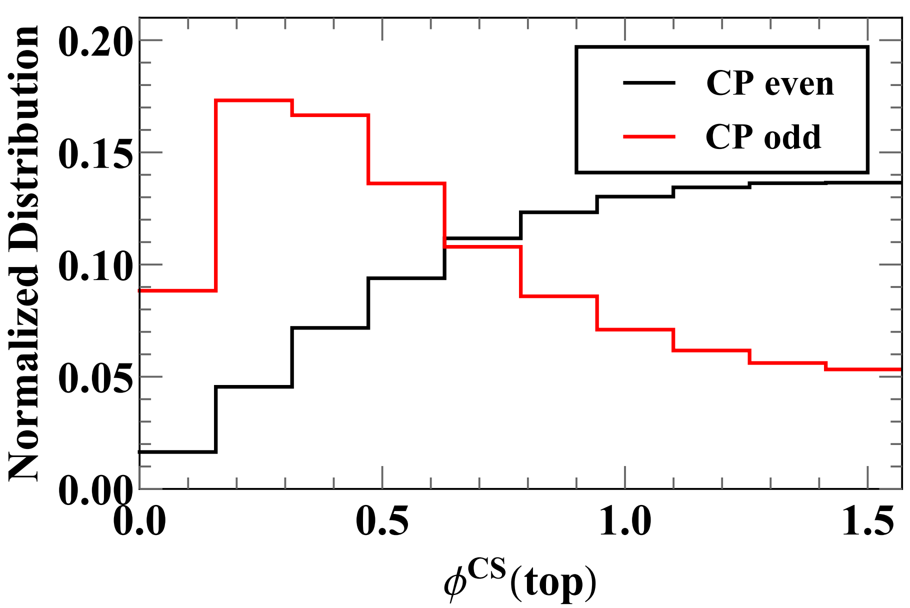
$$b_4(top) : \quad \frac{p_t^z p_{\bar{t}}^z}{|\,p_t\,|\,|\,p_{\bar{t}}\,|}$$



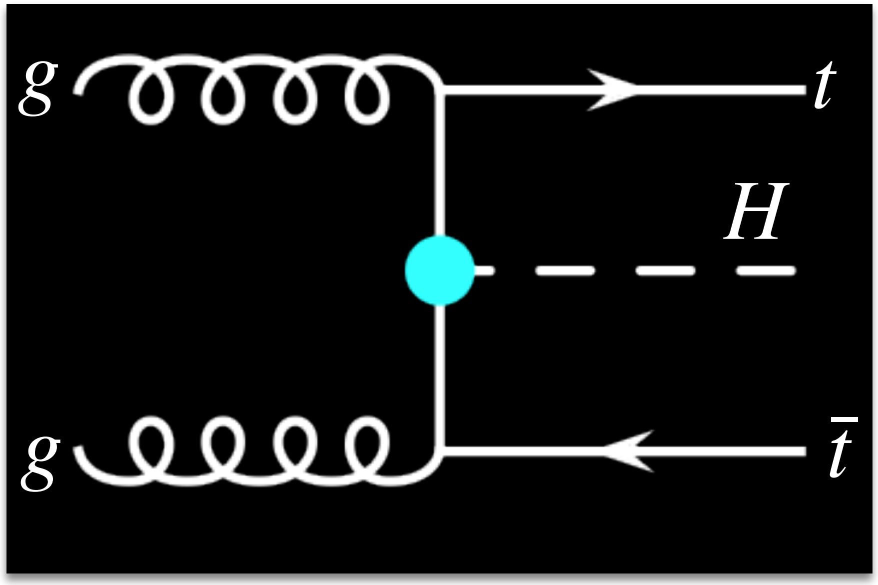
$$\Delta\phi^{exp}(top) : \quad |\,\phi(t) - \phi(\bar{t})\,|$$



$$\phi^{CS}(top) : \quad < \frac{\vec{p_t}}{|p_t|} - \frac{\vec{p_{\bar{t}}}}{|p_{\bar{t}}|}, \frac{\vec{p_{g_1}}}{|p_{g_1}|} - \frac{\vec{p_{g_2}}}{|p_{g_2}|} >$$



open angle between $t\bar{t}$ line and external bisector of gluons in $t\bar{t}$ rest frame

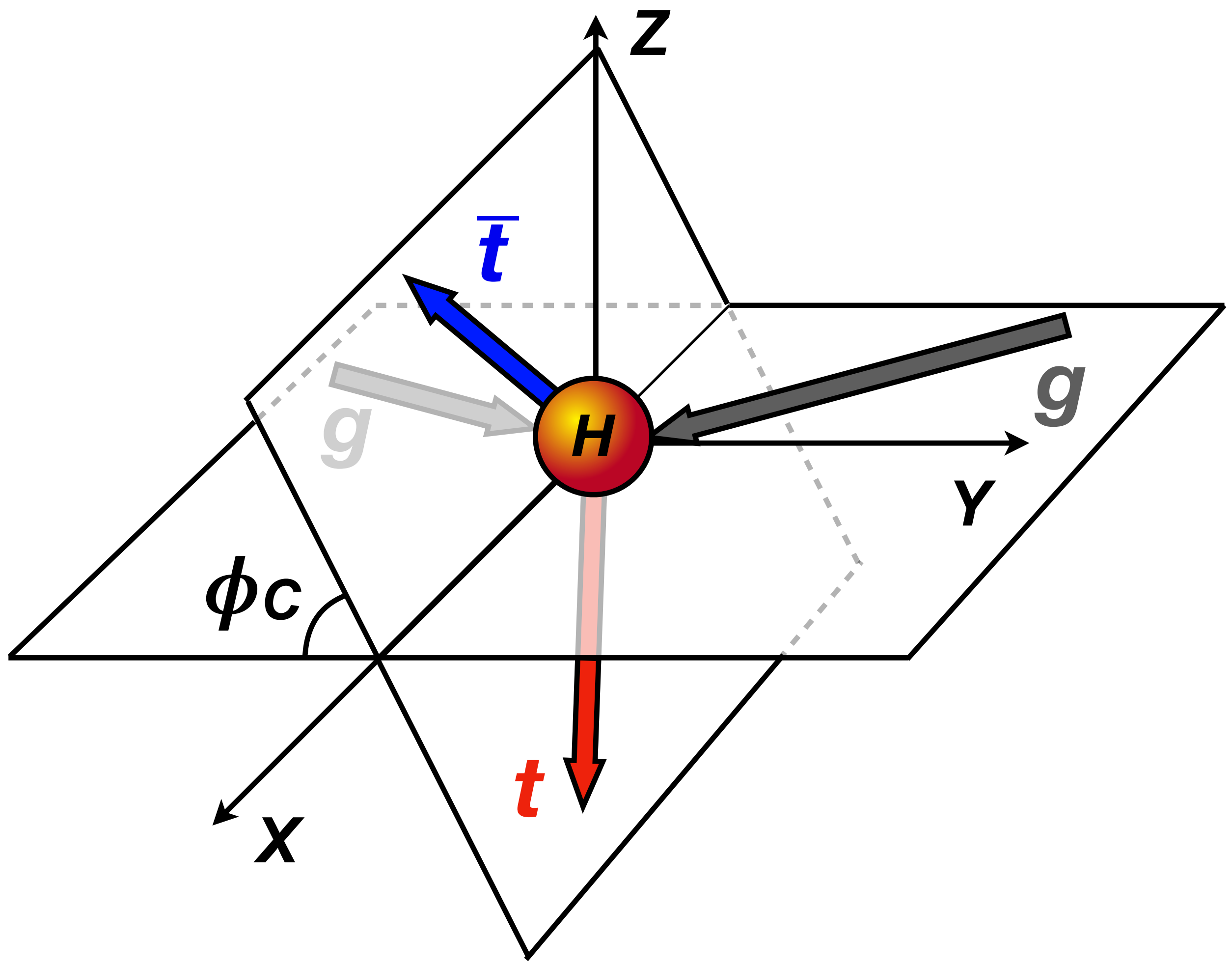


Decay plane correlation in ttH channel

QHC, Ke-Pan Xie, Hao Zhang, Rui Zhang, *Chin.Phys.C* 45 (2021) 2, 023117

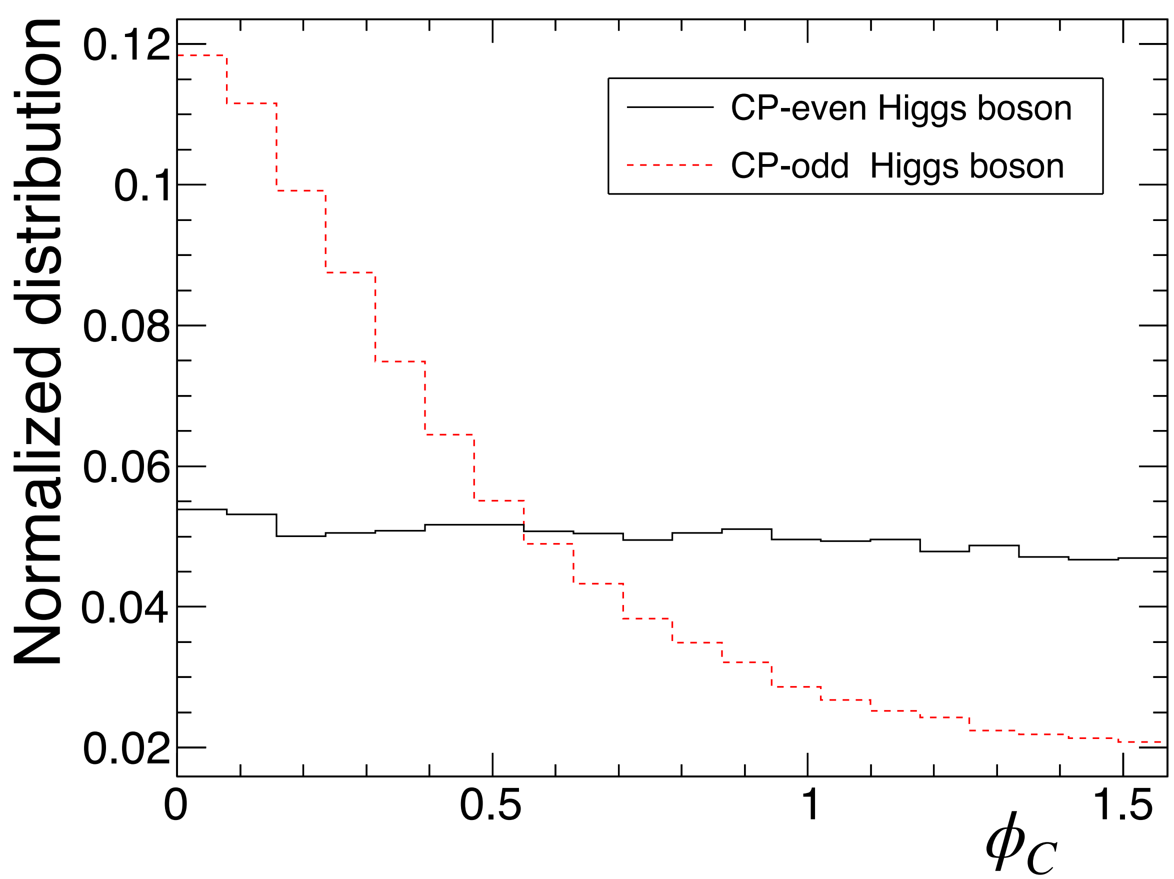
- We propose a new observable which is very sensitive to the parity nature of the *htt* interaction.

- P transformation from the Higgs point of view.



- A nature observable in the Higgs-rest frame:

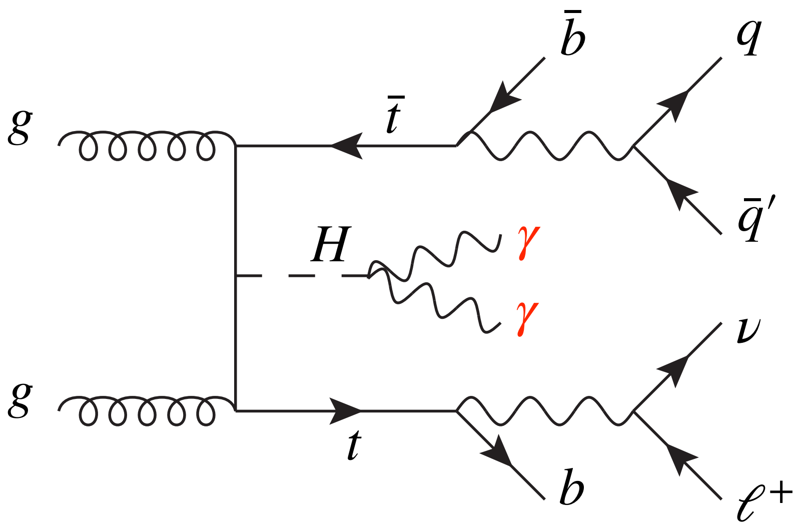
$$\phi_C = \arccos \left| (\mathbf{n}_{p_1} \times \mathbf{n}_{p_2}) \cdot (\mathbf{n}_t \times \mathbf{n}_{\bar{t}}) \right|$$

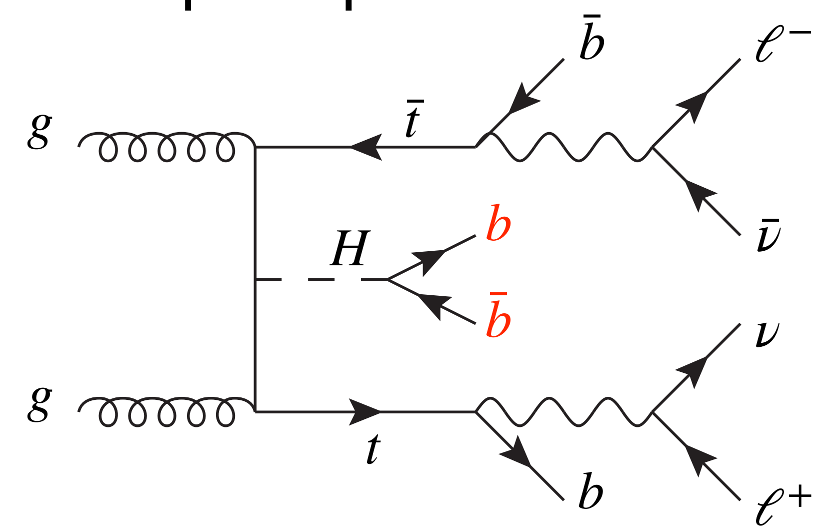


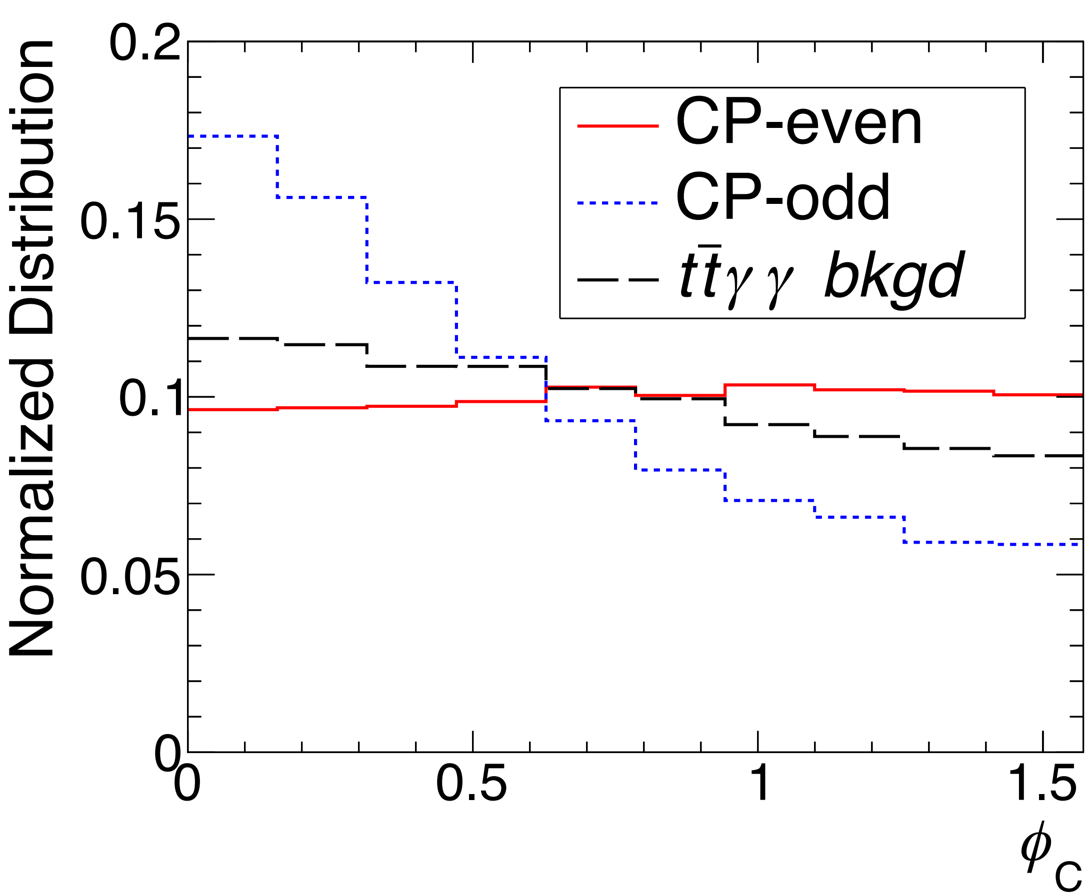
Diphoton Mode of Higgs decay

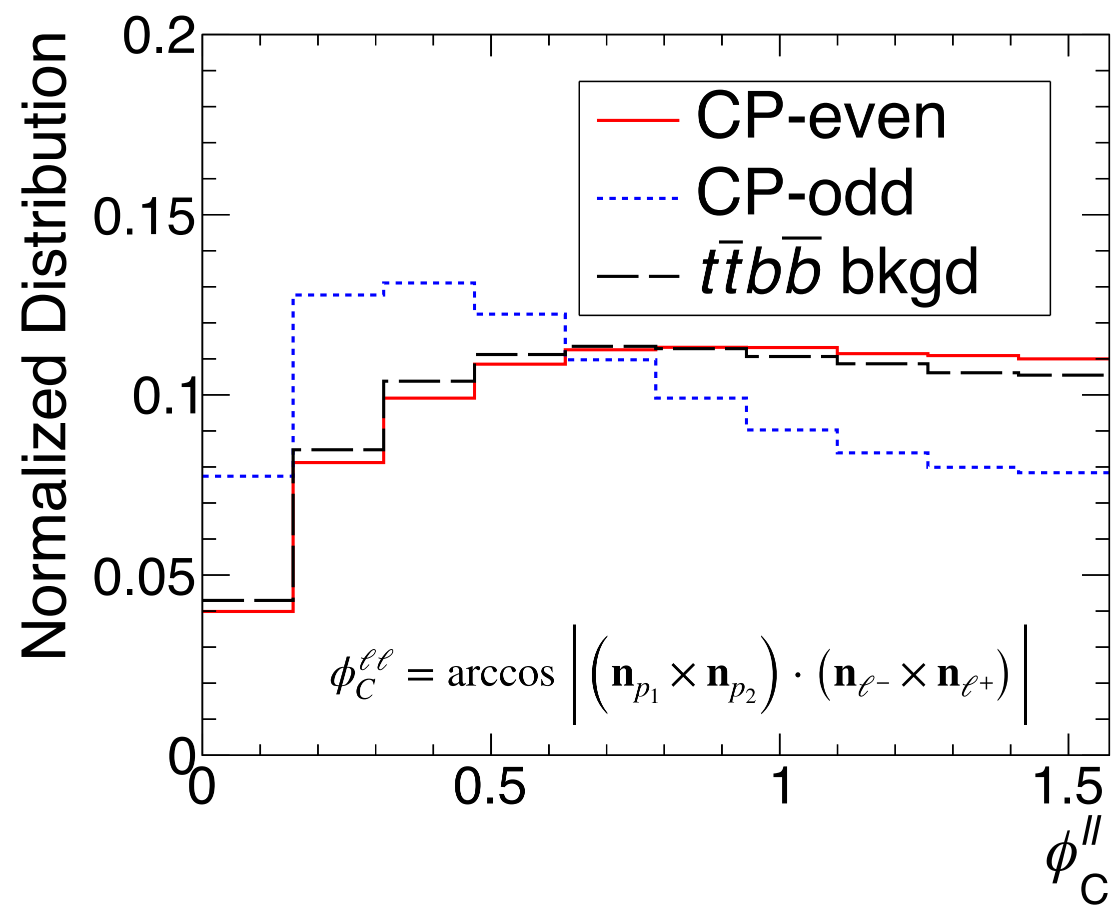
- Easy to reconstruct Higgs boson
- Clean signal but fewer events

- Large event number.
- The top anti-top plane replaced by the dilepton plane.



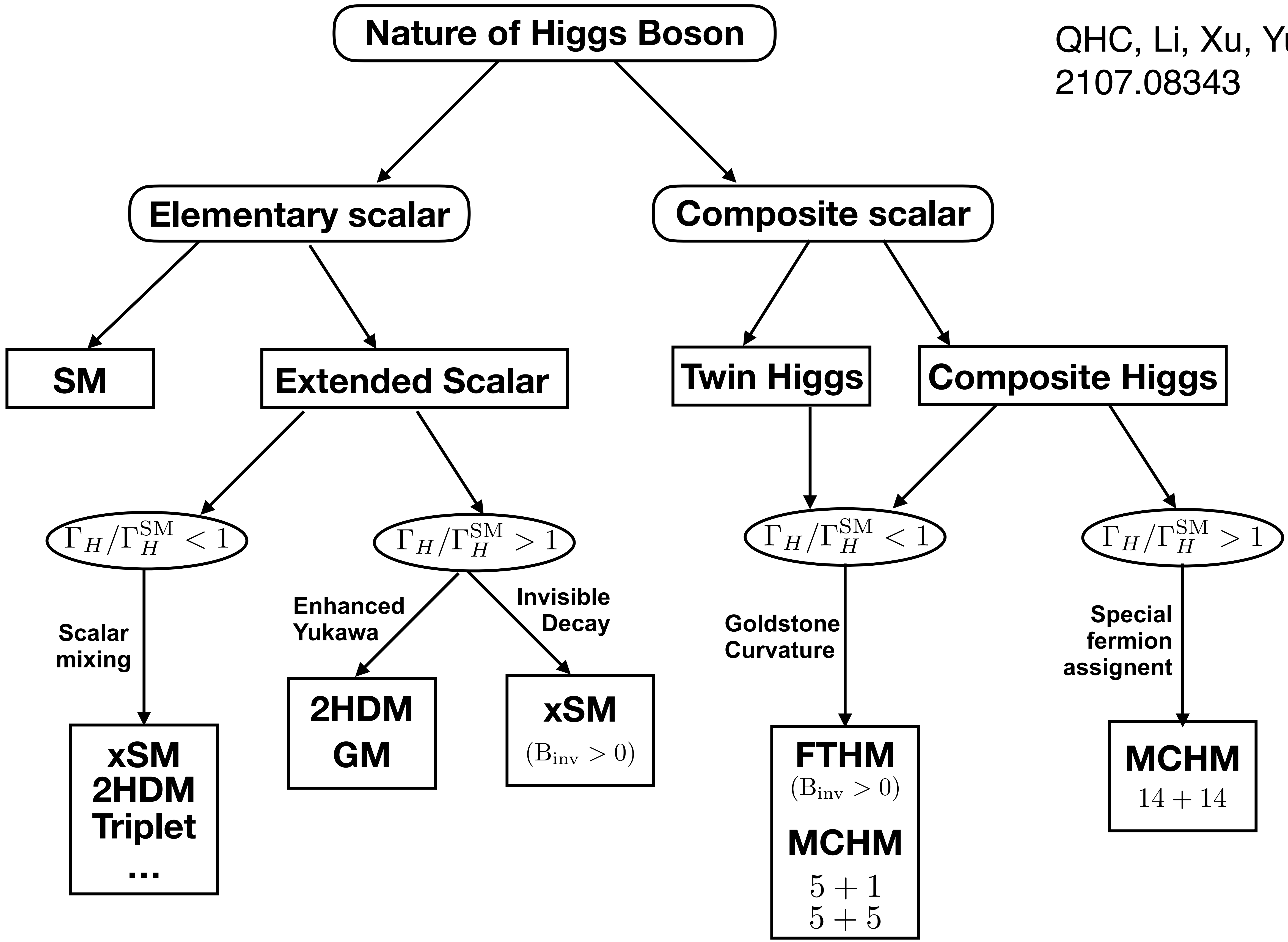






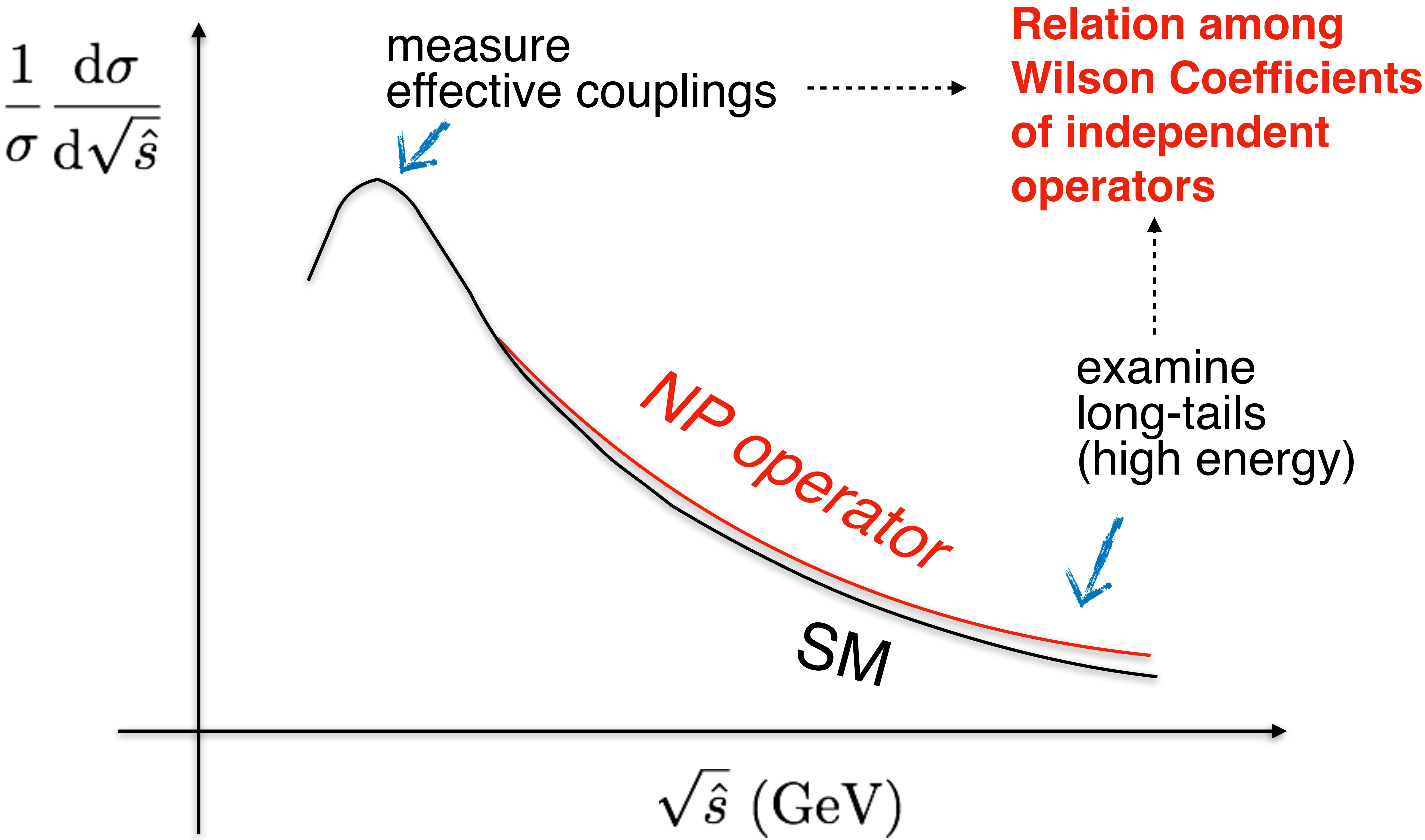
4. Higgs boson width

QHC, Li, Xu, Yu, 2107.08343



5. SMEFT analysis: Higgs &Top

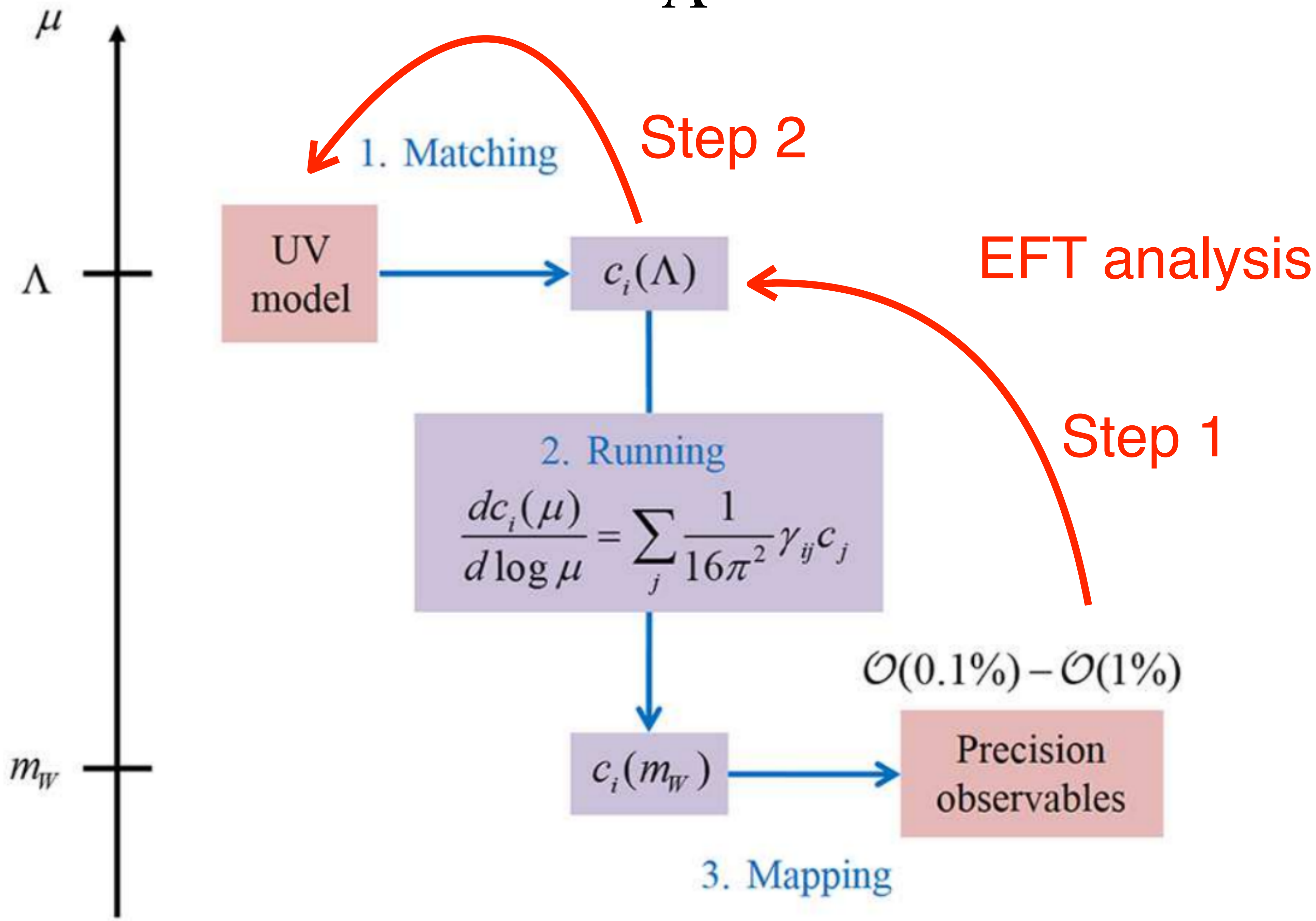
in case of no new resonances found in next 10 years



Top-Higgs physics in SMEFT

$$\mathscr{L} = \mathscr{L}_{\text{SM}} + \frac{c_i}{\Lambda^2}\mathscr{O}_i + \dots$$

Only consider dim-6 operators



Henning, Lu, Murayama, 1412.1837

SMEFT analysis

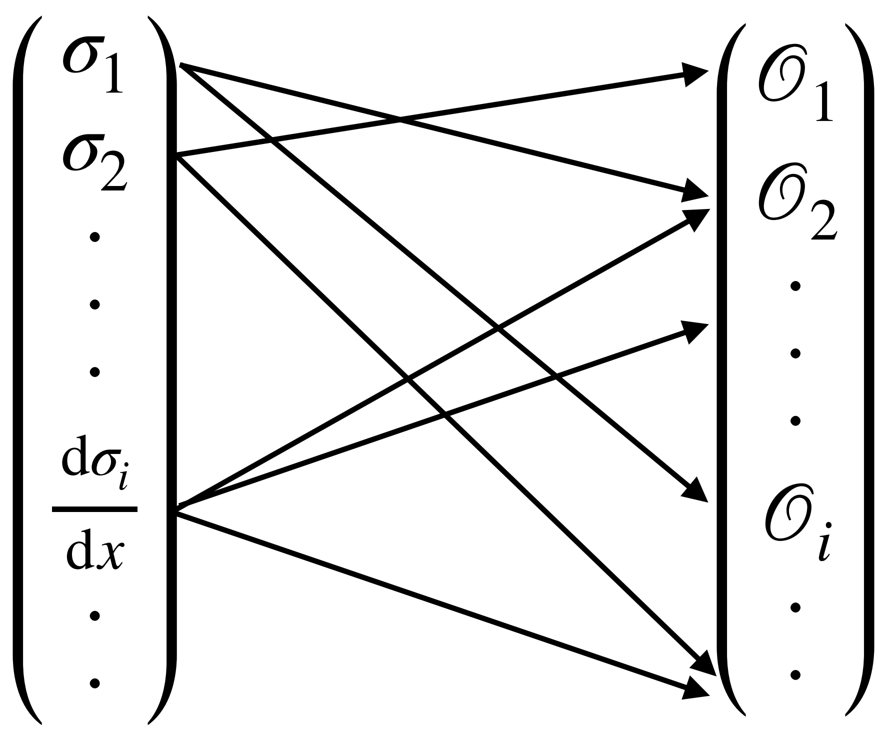
SMEFT

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)} O_i^{(6)}}{\Lambda^2}$$

Measurements

$$o_n^{\text{EXP}} - o_n^{\text{SM}} = \sum_i \frac{a_{n,i}^{(6)}(\mu)\, c_i^{(6)}(\mu)}{\Lambda^2}$$

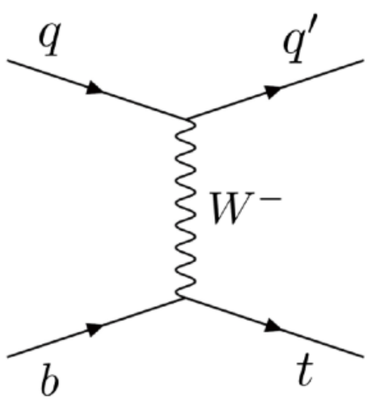
59 independent operators at **dim-6**



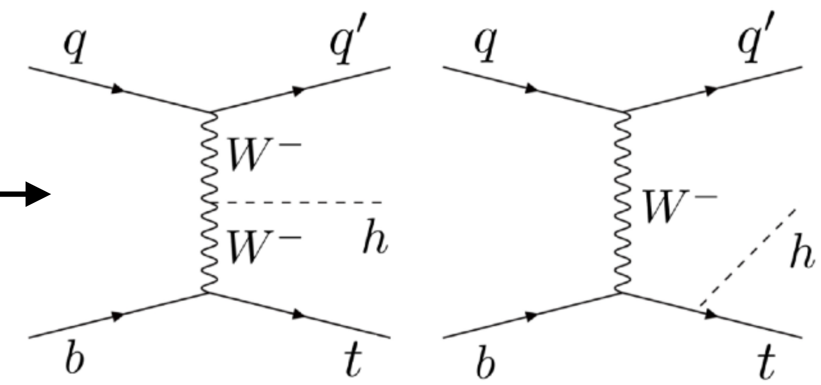
1) Linear (interference) or Quadratic (operator squared)? Dim-8?
2) RG running effect?
3) Operator Basis? Field and mass redefinitions?
4) QCD corrections? Operator mixings?

Single top production w/ and w/o a Higgs boson

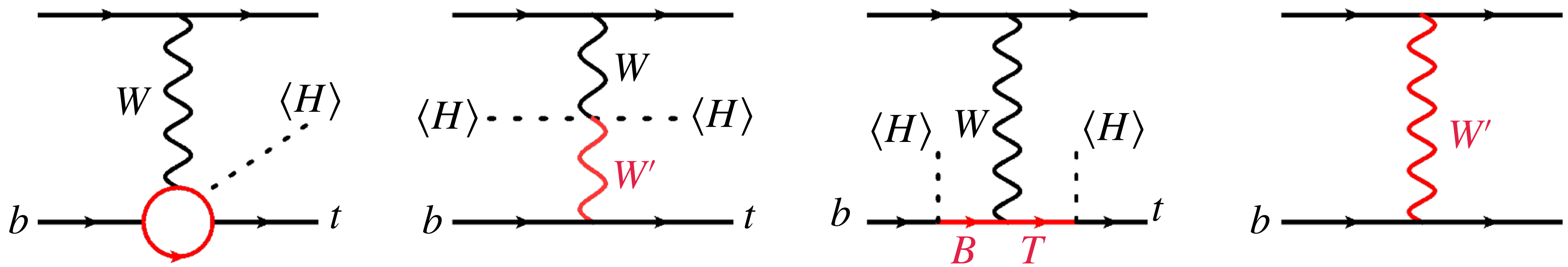
QHC, Jiang, Zeng, 2105.04464



Tree level correlation in the SM (↔)



The correlation in the linear analysis in SMEFT



$O_{uw} = (\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \tilde{\phi} W^I_{\mu\nu} + h.c.,$ WMD

QHC, Wudka, Yuan, 0704.2809

$O^{(3)}_{\phi q} = (\phi^\dagger i \overleftrightarrow{D}^I_\mu \phi)(\bar{q}_p \tau^I \gamma^\mu q_r) + h.c.,$ W-prime or Extra quarks

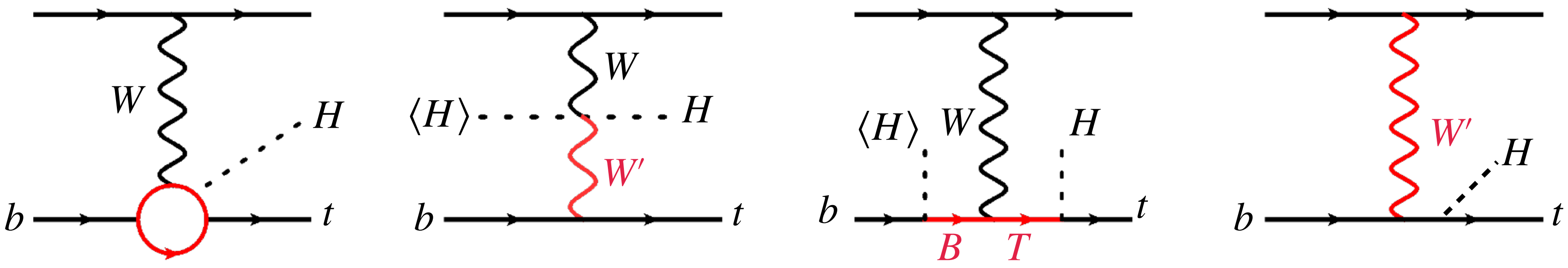
$$\left.\begin{aligned} O^{(1)}_{qq} &= (\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t) + h.c., \\ O^{(3)}_{qq} &= (\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_p \gamma^\mu \tau^I q_r) + h.c.. \end{aligned}\right\} \longrightarrow \begin{aligned} O^{(1)}_{3113} &= (\bar{q}_3 \gamma_\mu q_1)(\bar{q}_1 \gamma^\mu q_3) + h.c., \\ O^{(3)}_{3311} &= (\bar{q}_3 \gamma_\mu \tau^I q_3)(\bar{q}_1 \gamma^\mu \tau^I q_1) + h.c.. \end{aligned} \xrightarrow{\text{same interference}} O^{(3)}_{qq}$$

$$\sigma_t(\Lambda = 1\mathrm{TeV}) = \left[214^{+2}_{-1} - 13^{+2}_{-1} C^{(3)}_{qq} + 16^{+2}_{-3} C_{uW} + 13^{+1}_{-2} C^{(3)}_{\phi q}\right] \mathrm{pb}$$

Single top production w/ and w/o a Higgs boson

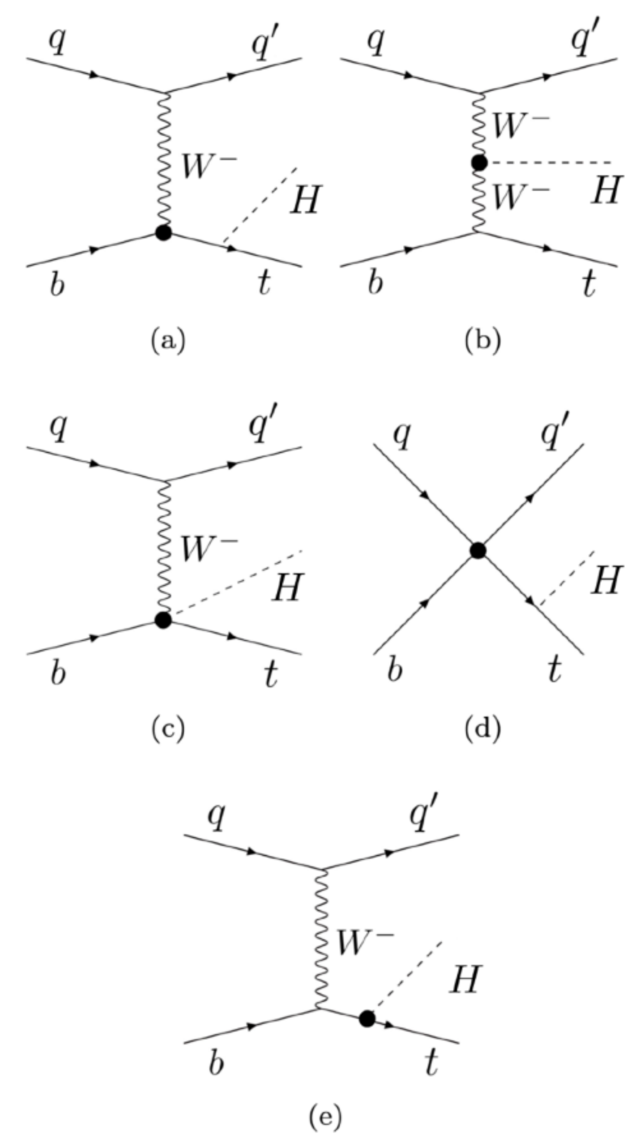
For comprehensive EFT analysis of the tHq channel, see 1804.07773 (Degrande,Maltoni,Mimasu, Vryonidou,Zhang)

Direct correlation induced by the three operators



More operators involved in tHq channel but bounded

Operators	Measurements
$O_{\phi D} = \left(\phi^\dagger D^\mu \phi\right)^* \left(\phi^\dagger D_\mu \phi\right)$	EWPT at LEP
$O_{\phi\Box} = \left(\phi^\dagger \phi\right) \Box \left(\phi^\dagger \phi\right)$	$gg \to H$ $H \to b\bar{b}$
$O_{u\phi} = \left(\phi^\dagger \phi\right) \left(\bar{q}_p u_r \tilde{\phi}\right) + h.c$	$gg \to H, \;\; gg \to t\bar{t}H$
$O_{\phi W} = \phi^\dagger \phi W^I_{\mu\nu} W^{I\mu\nu}$	$H \to ZZ^* / Z\gamma / \gamma\gamma$



The same three operators contributing predominantly in the tHq channel

$$\sigma_{tHq}(\Lambda = 1\text{TeV}) = \left[70.0 - 11.3^{+0.6}_{-0.3} C^{(3)}_{qq} + 22^{+1}_{-2} C_{uW} - 2.6^{+0.2}_{-0.2} C^{(3)}_{\phi q}\right] \text{fb}$$

Single top production w/ and w/o a Higgs boson

Three operators require at least three independent measurements; fortunately, single-top production provides richer info than expected.

$$\sigma_t = \sigma(tq) + \sigma(\bar{t}q) \longrightarrow O_{qq}^{(3)}, O_{uW}, O_{\varphi q}^{(3)}$$

$$R_t \equiv \frac{\sigma(tq)}{\sigma(\bar{t}q)} \longrightarrow O_{qq}^{(3)}, O_{uW}$$

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} \longrightarrow O_{uW}$$

$$\sigma_{tHq} = \left[-95.1 - 44.0 \times \frac{\sigma_{t+\bar{t}}}{\sigma_{t+\bar{t}}^{\rm SM}} - 266.0 \times \frac{A_{\rm FB}}{A_{\rm FB}^{\rm SM}} + 479.4 \times \frac{R_t}{R_t^{\rm SM}} \right] \text{fb}$$

Current

$$\sigma_{tHq} = \left[106.8 \pm 64.8\right] \text{ fb}$$

HL-LHC

$$\sigma_{tHq} = \left[74.3 \pm 45.4\right] \text{ fb}$$

The relation serves for checking the consistency of SMEFT.

Conclusion

It is very challenging but we need measure the HHH coupling from all possible ways to probe the scalar potential.

We are in the era of Higgs precision!

Precision measurements of Higgs couplings would shed lights on new physics beyond the SM.

Thank You!